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NASA CR-

A STUDY OF EXPERIMENTAL TECHNIQUES FOR PREALIGNING AND CLAMPING INERTIAL MEASUREMENT SENSORS WITHOUT MAJOR SYSTEM RECALIBRATION

FOSTER-MILLER ASSOCIATES INC.

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By

Allen E. Armstrong,

and

Dikrun Der Marderosian

October 1970

Prepared under Contract No. NAS 12-2015 by
FOSTER-MILLER ASSOCIATES, INC.
Waltham, Massachusetts

Electronics Research Center
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Waltham, Massachusetts

SUMMARY

Strapdown inertial guidance systems would offer significant advantages over gimballed systems if the sensor elements could be prealigned and replaced in the field without subsequent adjustment and/or verification.

The objective of this effort was to study techniques for prealigning and clamping inertial sensors. This included the design and fabrication of a highly accurate and stable clamping system to hold the sensor, and associated test hardware. Also included was the prepration of a detailed test plan to define facility requirements and test procedures. Additional effort was to be devoted to monitoring of the tests (to be conducted by NASA-ERC), resolution of the test data and recommendations for design changes to improve the performance of the clamp system.

The clamping system design was to include various interfaces for prealigning and mounting the sensor assembly. Three interchangeable adjustable clamp interfaces for prealigning the sensor and two fixed clamp interfaces for precise field replacement were to be evaluated.

Changes in the scope of effort and fund limitations resulted in the design of only one adjustable clamp interface and two fixed clamp interfaces. Reducation in scope of effort also precluded the completion of the final phases of effort which included fabrication, test monitoring and evaluation of the system performance.

The results presented in this report include a brief description of the basic systems considered, the detailed design of a prototype sensor - clamp assembly, with associated test hardware, a description of the various assembly components and their salient design features and a detailed , step-by-step test plan defining facility requirements and test procedures.

The design of the sensor-clamp assembly was sufficiently analyzed to assure a high probability of successful performance and the detailed steps outlined in the test plan should promote the recovery of accurate and useful data for evaluation.

It is recommended that the government fabricate and test the proposed system to evaluate the practicability of using field replaceable strap-down sensors without recalibration.

INTRODUCTION

Strapdown inertial guidance systems offer significant advantages over gimballed systems. The economic advantages, however would be greatly improved if the sensor elements could be prealigned and replaced in the field without subsequent adjustment and/or verification.

The objective of this study was experimental evaluation of techniques for prealigning and clamping inertial sensing units. This objective was to be achieved by a program of analysis, design, fabrication and testing of a test clamp closely simulating an actual sensor clamp. When the test clamp had been designed and verified analytically and the detailed test plan developed, the study was terminated.

The basis for the reported effort was established in a report of September 1968 entitled, Development of Optimum Clamp Combinations for Strap-down Inertial Measuring Units with Field Replaceable Sensors.[1]

The previous study included detailed analysis of the factors affecting the feasibility of strap-down sensor and clamp assemblies. Several sensor clamping systems were conceived and served as the models for the experimental techniques considered in this study.

The test clamp assembly is described in the "Description of the System" section. A more detailed description of the clamp design is given in the "Description of the Clamp Design" section along with the salient technical basis for the major design decisions. Finally, our conclusions and recommendations as a result of the work done to date are given. The specifications used as performance goals are listed in Appendix A.

DESCRIPTION OF THE SYSTEM

The basic system under consideration is shown in Figure 1. An inertial measurement unit (IMU) permanently affixed to the vehicle framework serves as the mounting block for a number of inertial sensors. The surfaces of the

[1] Prepared under NASA Contract No. NAS 12-591

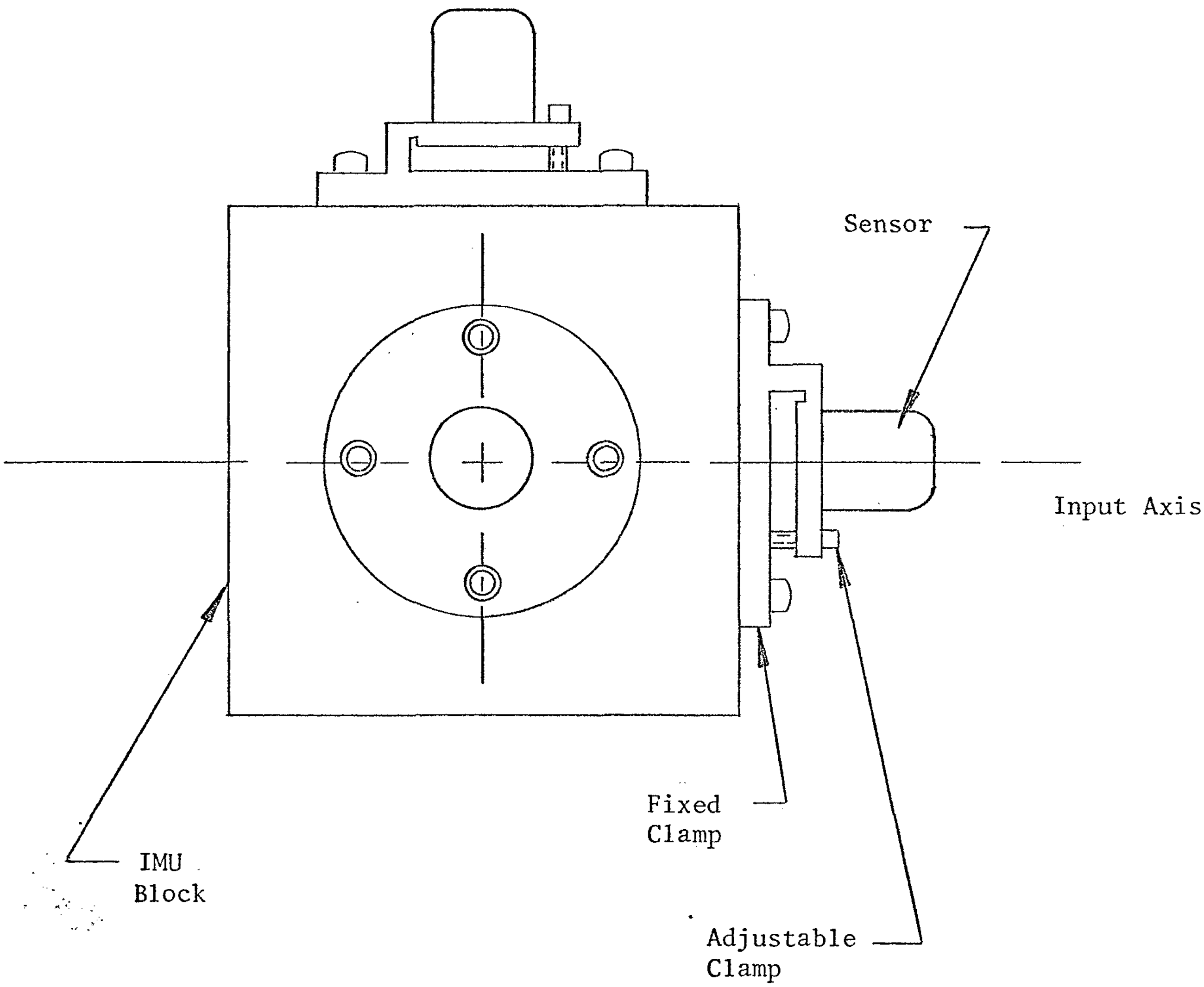

Figure 1. Schematic of Strapdown Inertial Measuring Unit (I.M.U.) Showing Clamps

IMU block are accurately machined and serve as the primary interface for alignment of the Input Axis (IA) of the sensors. An adjustable clamp interface is incorporated in the sensor clamp assembly to allow prealignment of the IA with respect to the lower surface of the assembly (fixed clamp interface) in the laboratory. Upon field replacement the fixed clamp surface is attached to the IMU block to establish the fixed clamp interface and align the sensor IA without additional adjustment. This "plane-on-plane" concept for field alignment was considered the most feasible approach from the standpoints of state-of-the-art machining capabilities, ease of field replacement and cost. The inclusion of dirt or dust at the fixed clamp interface, however, would cause gross misalignment of the sensor axes.

Two concepts for the elimination of dirt inclusion effects have been considered: (1) to provide rough but nevertheless flat and accurate surfaces at the fixed clamp interface and to mate the surfaces with a wiping action (similar to the wringing of gage blocks) to force dirt particles into the surface valleys, and (2) to deposit a thin, extremely uniform, soft coating (possibly gold or lead) to one of the interface surfaces and bring the surfaces together with no wiping, forcing the particles into the soft coating.

In addition to the fixed clamp concepts above, three adjustable clamp concepts were considered for prealigning the sensor in the laboratory. One concept employed replaceable gage elements at three locations for a purely selective fit adjustment technique. The second incorporated three compressible columns which were adjusted to various compressed heights and resulted in a purely material-deformation technique. The last utilized sliding wedges to adjust the height of three legs of the clamp for a purely mechanical-alignment technique. Figures 2, 3 and 4 show schematically the three adjustable clamp concepts considered.

Due to the fundamental differences between the adjustment concepts, experimentation with each would yield important data for the determination of optimum techniques. It was decided, however, that significant insight into the problems associated with each technique would evolve during experimentation with one configuration. The traverse wedge system was chosen for initial design and preliminary testing before designing the others. The design does, however, provide interfaces to allow incorporation of the other two techniques without major expense.

DESCRIPTION OF THE CLAMP DESIGN

The sensor clamp described in this report is a combination of two clamps. The adjustable clamp employs sliding wedges to permit adjustment of the input axis (IA) of the sensor. The fixed clamp permits separation and field replacement of the sensor and adjustable clamp on the IMU. This series of two clamps locates the IA in two angular degrees of freedom and the output axis (OA) in the remaining angular degree of freedom. Each clamp consists of one or more interfaces and means of applying sufficient clamping pressure to maintain contact at the interfaces: Reference to the design layout, Figure 5, will facilitate understanding of the following discussion.

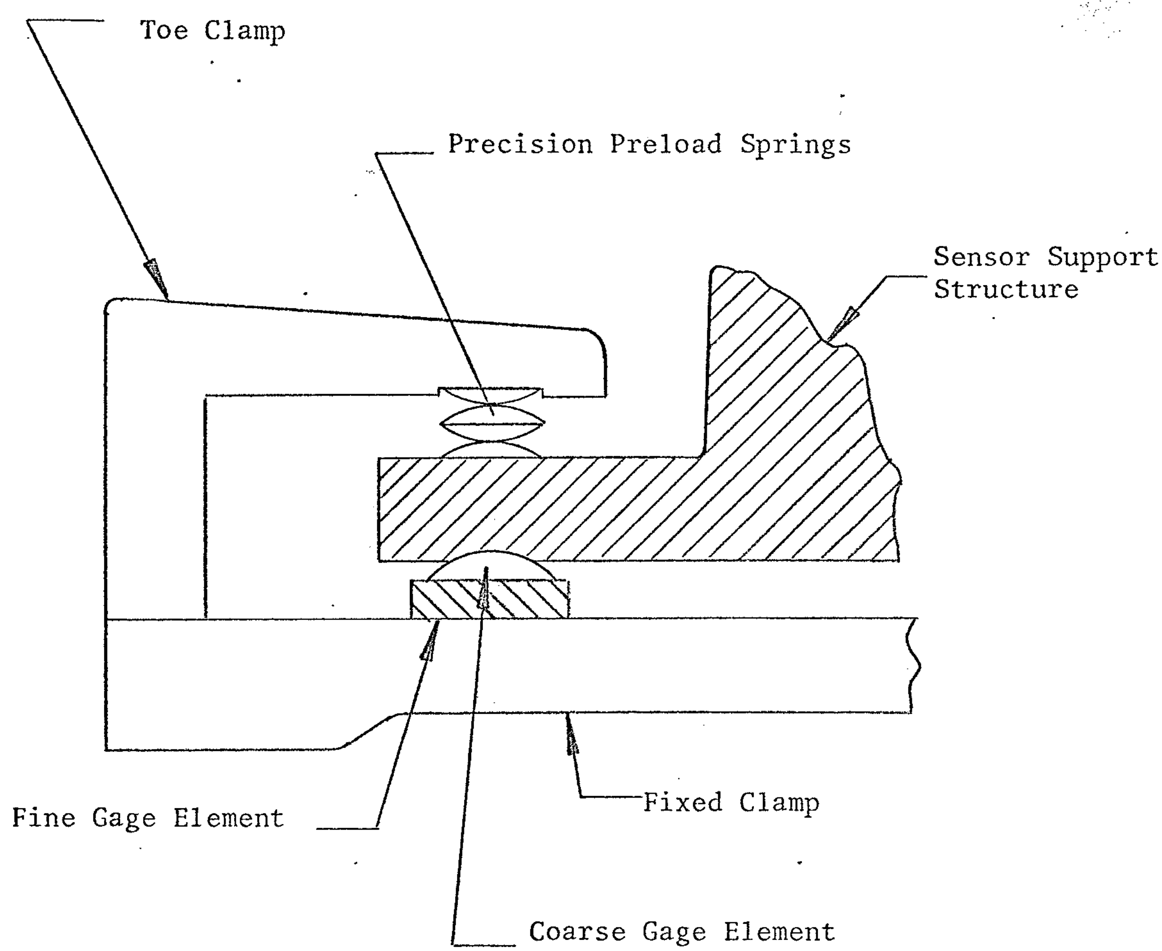

Figure 2. Selected Fit Adjustment Using Precision Gage Elements

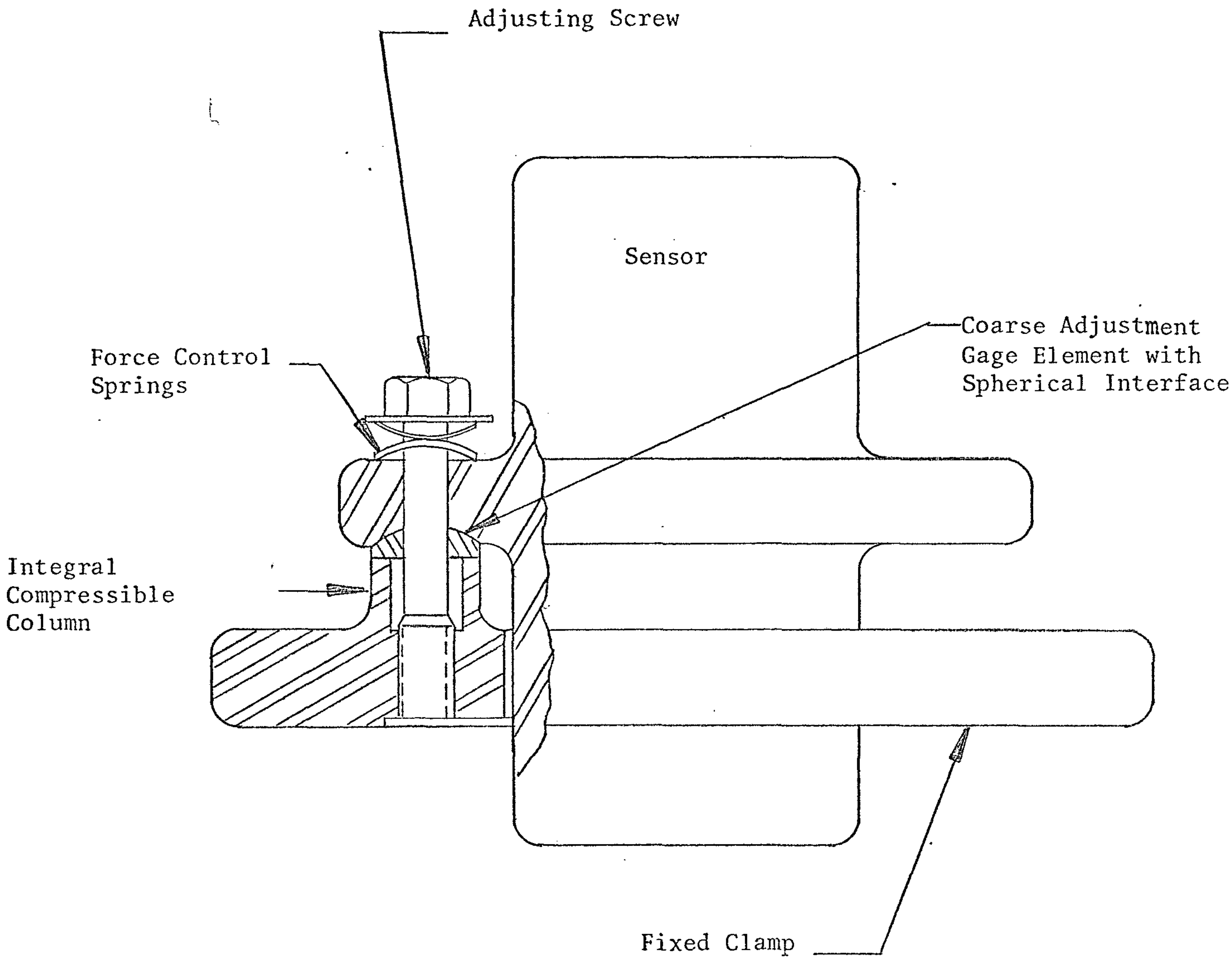

Figure 3. Compressible Column Concept

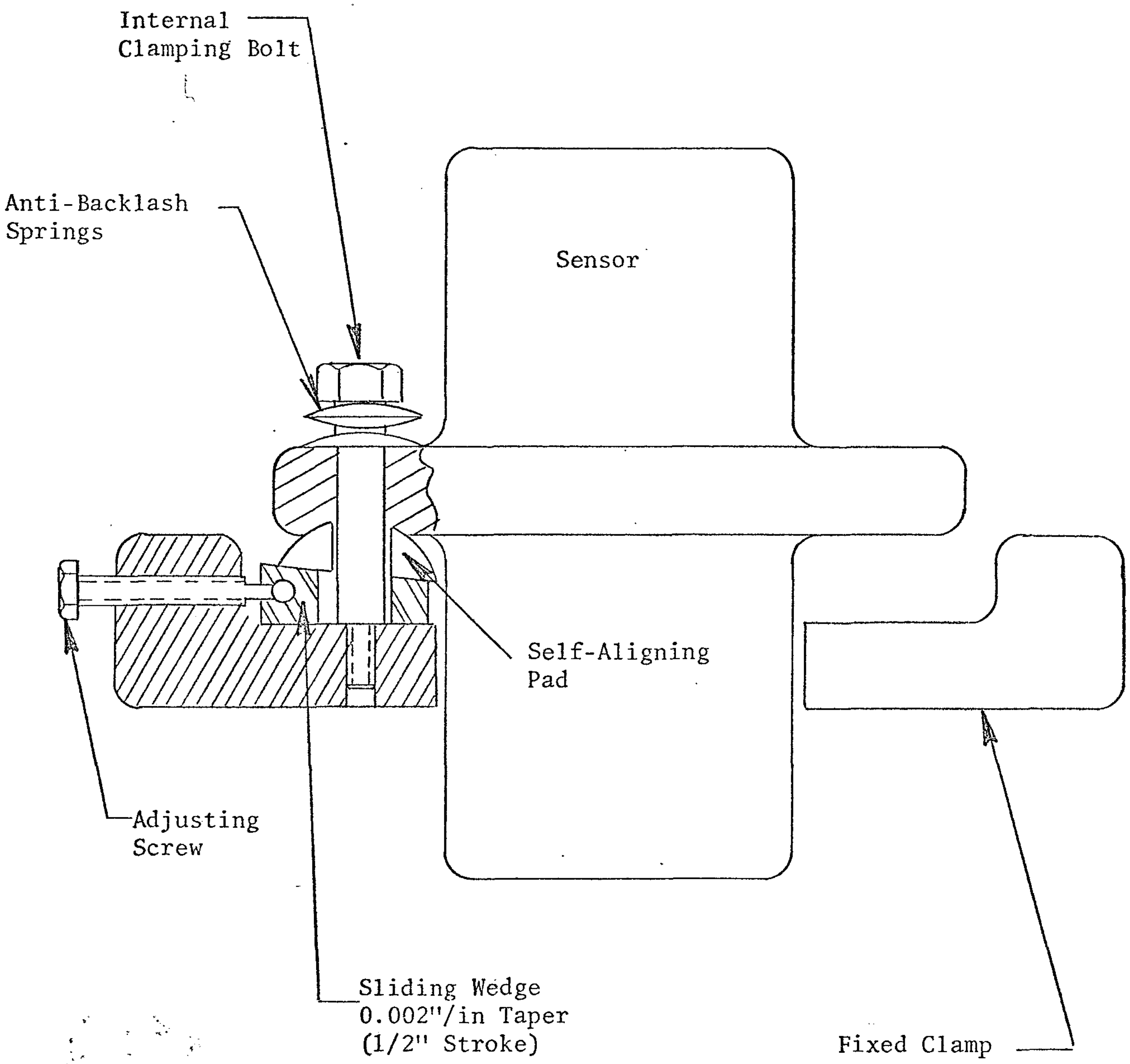

Figure 4. Transverse Wedge Adjustment Concept

DRAWING NO. INDEX

NASA 6817-01	IMU BLOCK	
	-02	FIXED CLAMP RING
	-03	WEDGE
	-04	SPHERICAL GAGE BLOCK
	-05	RETAINER SPRING
	-06	GUIDE RING
	-07	SPRING CLIP
	-08	SHOULDER SCREW
	-09	DOWEL PIN
	-10	T-BOLT
	-11	LEAF SPRINGS
	-12	CASTLE NUT
	-13	SPHERICAL SPRING PAD
	-14	SENSOR BLOCK
	-15	ADJUSTMENT SCREW

STANDARD PARTS INDEX

No.	PART	DESCRIPTION	MANUFACTURER	NAME OR CAT. No.	QTY
1s	SHOULDER SCREW	1/4 DIA. NOM x 3/8 LG. SHOULDER, TH'D. No. 10-24 UNC x 3/8 LG. SOC. HD., SELF-LOCKING. ALLOY STEEL	—	—	3
2s	BELLEVILLE SPRING WASHER	1/2 O.D. x 1/4 I.D x .018 TH'K. RELAXED HT.-.034. ALLOY STEEL	ASSOCIATED SPRING CORP.	B0500-018	33
3s	MACHINE SCREW	SOC. BUTTON HD. No. 4-40 UNC-3A THD. 1/4 LG. SELF-LOCKING. STEEL	—	—	6
4s	HEX NUT	No. 10-32 UNF-3B THD. SELF LOCKING	ESNA	79 NTM 02	6
5s	COTTER KEY	1/32 DIA x 1/2 LG. STEEL	—	—	6
6s	O-RING	3/4 I.D. x .060 DIA. BUNA-N OR VITON.	PARKER	2-18	1
7s	MACHINE SCREW	FLAT HD. No. 2-56 UNC x 1/4 LG. STEEL	—	—	1
8s	CARTRIDGE HEATER	10 WATT, 115 VOLT	MINCO	HBA 10W115	1
9s	CARTRIDGE HEATER	125 WATT, 115 VOLT	WATLOW	J2E61	3
10s	HEATER	5 WATT 7/8 SQ. IN.	MINCO	THERMOFOIL	1
11s	THERMOCOUPLE	IRON-CONSTANTIN .015 DIA. WIRE	OMEGA	1RCO-015	9
12s	SET SCREW	SOC. TYPE No. 8-32 UNC-3A TH'D. 1/4 LG. OVAL POINT. STEEL	—	—	3

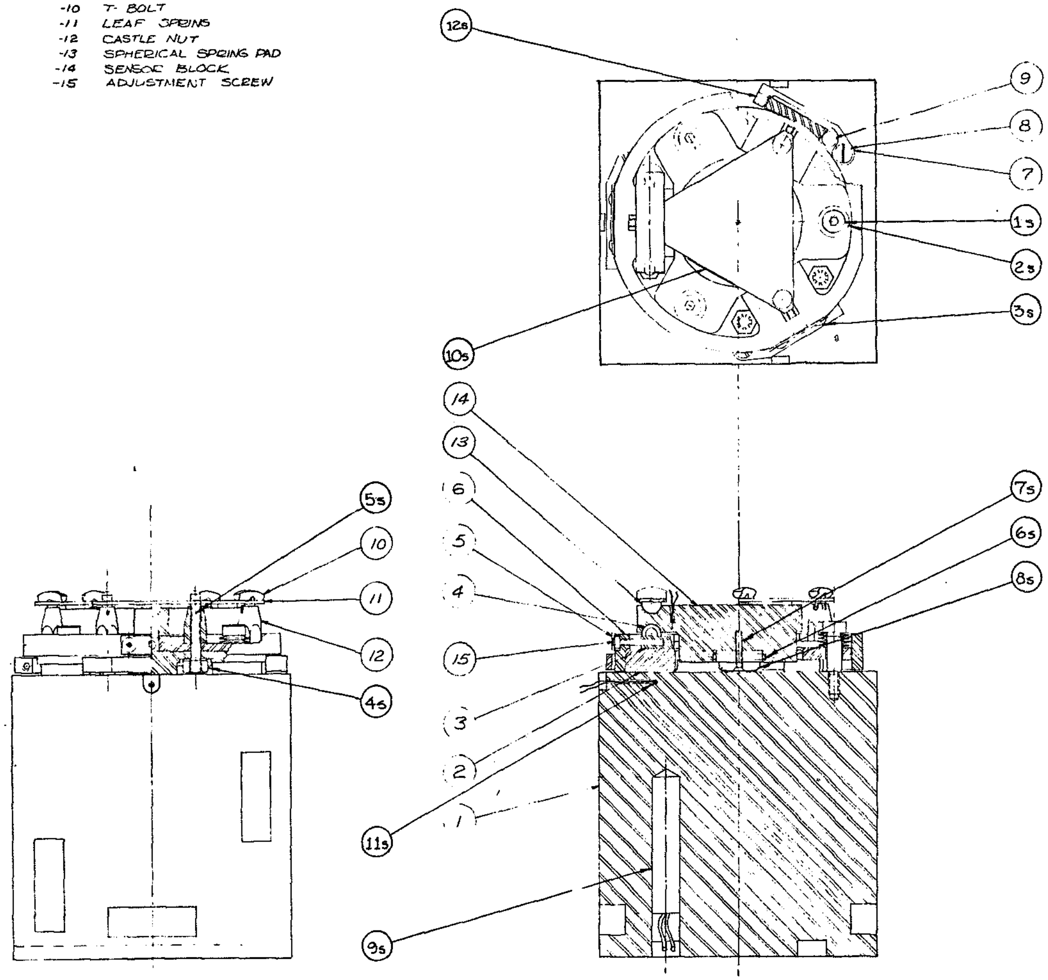

Figure 5. Design Layout.

The fixed clamp has interfaces with the IMU block at 1) the top surface of the IMU block and, 2) surfaces of the 3 locating pins permanently pressed into the IMU block. Contact pressure is maintained at these interfaces by the 3 belleville washer stacks and the 3 spring clips (7). The remaining parts are part of the adjustable clamp. It is conceptually simpler, however, to describe the clamps in terms of input and output axis location functions.

Input Axis Location. - - The input axis of the sensor is desired to be perpendicular to the top surface of the IMU block. This perpendicularity is established by three sensor legs above the IMU block surface. Adjustment of the stack heights by lateral motion of the wedges (3) adjusts tilt of the IA. Three leaf springs (11) acting on spring pads (13) provide contact pressure on the stacks. Rough adjustment of stack height is achieved by selection of the spherical gage block (4) to bring the stack height within .0005 of the others. A more detailed discussion of IA alignment problems and solutions follows.

Fixed Clamp Interface - - The fixed clamp interface, at which separation occurs for sensor replacement, consists of the three pads on the lower side of the fixed clamp ring (2) contacting the upper surface of the IMU block (1). Since this interface will be separated and rejoined under non-clean conditions in the field, inclusion of dirt in the interface is a problem. A hard dirt particle one micron in diameter could cause a 3 sec error in IA alignment. To alleviate this problem the lower surface of the fixed clamp ring (2) was purposely left somewhat rough at 32 microinch rms. If a wiping rotation is used in bringing the sensor/clamp into position on the IMU block, dirt on the order of one micron may be swept into the valleys of the surface roughness. Larger dirt particles must be wiped from the surfaces prior to emplacement of the fixed clamp.

By coating the lower surface of the fixed clamp ring (2) with a thin (.001) layer of a soft metal such as gold, an alternative method of dirt control may be studied. Direct placement of the clamp with no wiping would force the dirt particles into the soft metal coating, miniminzing their effect on alignment. Because the coating is extremely thin, overall stiffness is not appreciably affected even though elastic modulus of the coating is relatively low.

Fixed Clamp Contact Pressure. - - Contact pressure at the fixed clamp interface is maintained with 10% of a nominal 130 lb. total by three stacks of belleville washers retained by three shoulder screws. This clamp force is controlled in order to prevent distortion of the fixed clamp ring by excessive or uneven clamp pressure. Stress conditions in the fixed clamp ring and their implications on belleville stack location are analyzed in the Data Package submitted under separate cover. Adjustment of clamping pressure is made by adding or subtracting one belleville washer from the nominal eleven washers per stack. The 130 lb. total contact pressure was selected to prevent separation of the fixed clamp interface under a 50g vertical shock.

The shoulder screws (1 s) perform only the function of loading the belleville washers. They are given sufficient clearance in the fixed clamp ring (2) to allow this ring to be located solely by its bolted connection (by T bolts (10)) to the guide ring (6). The lateral location of the fixed clamp ring is unimportant, as long as it does not change after adjustment.

Adjustment Wedge. - - The IA adjustment stack above the interface at the IMU block surface consists of the fixed clamp ring (2), the adjustment wedge (3), the spherical gage block (4), and the sensor leg (14), containing the socket for the spherical gage block.

This stack was designed as short as possible to minimize thermal growth differences in the three stacks as a result of temperature gradients.

Each adjustment wedge is tapered .004 per inch, and moves 0.20 inch radially, giving a stack height difference of .008 as the range of wedge adjustment. This is equivalent to 1.2 arc minutes. The desired adjustment range of 25 arc minutes is achieved by selecting one of 32 spherical gage blocks as a rough adjustment. Adjustment gain is 7^{o} of adjustment screw (15) rotation per arc second of IA motion. Resolution of this adjustment is, however, limited by stick-slip friction in the wedge, spherical block and seat interfaces, and is 0.4 arc second for a friction coefficient of 0.2.

Spherical Gage Block. - - The spherical gage block (4) was included in the adjustment stack to permit small angular changes in IA tilt relative to the wedge surfaces, while distributing the sensor support load over a large enough area to keep contact stress below the micro-yield stress. A close fit between the ball and socket cavity is necessary to keep the Hertz contact stress low. The radial fit was required to be between zero and .0001 inch diameter difference to prevent too low a lateral resonant frequency and this was sufficient from a stress standpoint.

Clamping Load. Clamping load of 17 pounds per adjustment stack is provided by the leaf springs (11) which keep the load constant within ± 5% over the adjustment range of the wedge. When different gage balls are inserted, the castle nuts (12) are turned one flat (1/6 turn) for each .003 inch change in gage block thickness. The leaf springs are designed for quick removal by depressing the "keyhole" end .020 inch to clear the groove in the T-bolt (10) and then sliding the spring out of engagement at its forked end.

The load balls (13) are intended to minimize the moments exerted on the sensor leg by spring contact eccentricity.

Dummy Sensor Configuration. -- The sensor block is not intended to to represent the physical configuration of any available inertial sensor, but is intended to be the most rigid configuration supporting the three sensor legs, having its center of mass in the plane of the gage balls. The dummy sensor is viewed as a testing fixture which permits accurate determination of the clamp alignment capabilities, unobscured by distortions in the sensor. It is important to note that it is unlikely that any real sensor would approach the rigidity and symmetry of the dummy sensor. It is in fact highly likely that a real sensor would have more distortion than the rest of the clamp. This may impose severe limitations on the accuracy of any strapdown gyro sensor/clamp unit, but the present task is limited to clamp evaluation; thus the selection of a rigid block dummy sensor.

Adjustment Screws. - - To prevent blacklash in the wedge adjusting screw (15) which would introduce unwanted changes in IA alignment, the threads are lapped threads, to a backlash of .0001/.0005 inch giving a 0.2 sec shift maximum as the wedge moves within the backlash zone. Anti-backlash springs were not employed because of a lack of space. Backlash in the screw-to-guide ring interface is prevented by the loading spring (5) which has an aperture for insertion of the wrench to turn the adjustment screw (15). This spring-load also serves to lock the screw (15) against rotation under vibration conditions.

OUTPUT AXIS LOCATION

The Output axis is located to an accuracy of 60 arc seconds by non-adjustable interfaces. Because of the built-in accuracy required, and the large number of parts whose locations are affected by machining tolerances, these tolerances must be held within limits that are presently at the limit of the state-of-the-art. An advantage of the location method employed is that the angular error at any level in the clamp assembly is the arithmetrical average of the angular errors introduced by each of the three interfaces at that level.

Fixed Clamp Interface. - - OA orientation of the fixed clamp is provided by contact between three radial faces on the guide ring (6) and three locating pins pressed into the top surface of the IMU block. The 3 point contact obtained is determinant without being redundant. Contact is maintained by pressure from the spring clips (7) which allow limited radial motion of the guide ring (6) relative to pins (9). The spring force exerted by these clips must be great enough to prevent separation under a 50g side shock load. The set screw tensioning method was chosen to allow the spring to be brought to maximum tension without overstressing it. Spring pressure of 90 lb. each is sufficient to prevent separation of the OA contacts under 50g side shock load. This is attained at a maximum spring stress of 80,000 psi. Because of the line contact between the dowel pins and the OA alignment lugs, a high stress exists at the contact line. Hertz analysis gives a stress of 180,000 psi during a 50g shock condition tending to compress the contact interface.

Remaining Clamp Interfaces. - - The guide ring (6), which is located by the pins in the IMU block, contains three radial slots in which the IA adjustment wedges (3) and the spherical gage blocks (4) slide. The wedges play no part in locating the OA, but the spherical gage blocks, whose flattened sides fit closely in the radial slots, locate the sensor's spherical seats. The OA error budget is split between the following:

1) IMU block face to dowel pin centers

2) Dowel pin daimeters

3) Guide ring lug faces to guide ring slot

4) Guide ring slots to ball centers

5) Socket centers to sensor mirror

Tolerances of .0001 (about 10 arc seconds) must be held throughout this system.

ALIGNMENT MIRRORS

Mirror surfaces (reflective 2 rms finish) are provided in six locations to determine sensor to IMU alignment and to isolate misalignments.

Input Axis mirrors. - - The 1) top surface of the IMU block 2) top surface of the fixed clamp ring, and 3) top surface of the sensor are input axis mirrors.

Output Axis mirrors. - - The output axis mirrors are 1) one side of the IMU block 2) a polished flat on the guide ring, and 3) one side of the sensor block.

HEATING SYSTEM

Simulation of a variety of symmetrical and asymetrical thermal gradients is made possible by inclusion of three heaters sized to provide steady state thermal gradients of 1°F per inch. Three cartridge heaters are imbedded in the IMU block, one below each sensor support stack, and may be used singly or in combination to provide heat flow to the sensor. Reverse heat flow can be established by use of the central sensor heater and one or two printed-circuit heaters glued to the unpolished sides of the sensor. Thermocouples are provided in 9 locations in the support stacks to measure the thermal gradients established.

CONCLUSIONS AND RECOMMENDATIONS

The sensor clamp described in this report has been completely designed and sufficiently analyzed to assure a high probability of successful performance. Detailed fabrication drawings and a specific and detailed test plan have been completed. The work remaining to accomplish the objective of the program is fabrication and testing of a clamp assembly. Completion of this work would add to present knowledge about the state-of-the-art of precision sensor clamping.

It is recommended that the program be completed by fabricating and testing the clamp assembly to determine its performance characteristics and practicality for field use.

Appendix A

SPECIFICATIONS

The following items served as design goals for the test prototypes and provided guidelines for the test procedures which were subsequently recommended.

1. Alignment Accuracy of I.A & O.A

   The goal will be to locate the I. A. within a cone with a half-angle of 3.0 sec about a specified nominal axis. The O.A. shall be located within a cone having a half-angle of 60 sec about a specified nominal axis.

2. Prealignment

   I.A. and O.A prealignment capability conforming to 1. above with I.A. position adjustment resolution of 1 sec.

3. Repeatability

   Prealigned clamp assemblies must be inserted, clamped, tested for alignment, and removed 4 times within a period of 12 hours on the same I.M.U. prototype.

4. Acceleration

   (a) Shock 50 g's for 10 msec

   (b) Steady Centrifugal 15 g's for 15 sec

   (c) Steady Centrifugal 3 g's for 24 hrs.

   The goal will be to maintain alignment after condition (a) and during (b) and (c). Tests will be confined to measurements following the acceleration conditions.

5. Vibration

   The assembly will be designed to withstand the following vibration conditions while providing alignment. Alignment will be checked following each test condition.

(a) Sinusoidal	0.5 in	5-17 cps
	7.0 g	17-22 cps
	5.0 g	22-400 cps
	7.5 g	400-3000 cps

(b) Random $0.05\ g^2/$ cps 20-400 cps

$0.12\ g^2/$ cps 400-2000 cps

6. Acoustic Excitation

The assembly will be designed to provide alignment in the presence of the following acoustic excitation:

Frequency, cps	Sound Pressure Level, d.b. re .0002 dynes/cm^2
Overall	154
37.5-75	128
75-150	132
150-300	146
300-600	146
600-1200	147
1200-2400	148
2400-4800	148
4800-9600	148

7. Thermal Conditions

The assembly shall be designed to provide alignment under the following thermal conditions:

(a) Ambient temperature cycling between $40^{o}F$ and $180^{o}F$

(b) With temperature gradients in critical elements of the assembly of $1^{o}F$/inch for short periods (e.g. 10 sec) and $1/4^{o}F$/inch for long periods.

8. Insertion and Removal

The assembly shall be designed so that the sensor can be inserted or removed in a time period of 1 hour or less with normal dexterity with assistance of manually portable equipment, if necessary.

9. Physical Characteristics

(a) The design goal for the weight of the assembly will be that it not exceed 2.5 times the dummy sensor weight.

(b) The goal for volume will be that the assembly not occupy more than 4 times the volume of the dummy sensor.

The above goals do not include portions of the simulated I.M.U. which are peculiar only to the test system.

10. Pressure

The assembly shall be designed to maintain alignment in an environment where the ambient pressure is 10^{-5} Tor.

As a result of analysis performed during Phase I of this project, (Reference: Howland, J.S.; Goldstein, S.R.; and DerMarderosian, D. "Development of Optimal Clamp Combinations for Strapdown Inertial Measuring Units with Field Replaceable Sensors" prepared under NAS 12-591) additional design goals were determined from the specifications. These are as follows:

1. Stresses in all parts affecting alignment of the input axis should be limited to one half the micro-yeild stress (20,000 psi for stainless steel chosen for most components) in order to prevent creep, or long-term instability.

2. Stiffness of all parts of the clamp should be sufficient to prevent resonant frequencies below 6 khz, or twice the test vibration frequency.

3. Finish of all surfaces at which motion occurs during IA adjustment should be smooth enough to prevent excessive stick-slip friction which would limit resolution.

Appendix B

TEST PLAN

Introduction

The purpose of the test program is to measure the angular misalignment of the sensor and clamp surfaces relative to the IMU block. In addition to an initial alignment check, the effect of external disturbances (such as heat, vibration, etc.) must also be observed experimentally. The design of the clamp will be judged on the ability of the test unit to establish and maintain the alignment of the IA and OA within the allowable error band. The allowable misalignment and the environmental disturbances under which the clamps must maintain alignment is given in Appendix A.

Specifically, the test plan consists of a series of tests which measure - under different conditions - the following four angles.

(a) The angle between the mirrored surfaces on top of the IMU block and the interface piece (Figure B-1). This determines the I.A. misalignment (magnitude and direction) due to the fixed clamp.

(b) The angle between the mirrored surfaces of interface piece and the top of the sensor. This determines the I.A. misalignment due to the adjustable clamp.

(c) The angle (in the horizontal plane) between the mirrored surfaces on the side of the IMU block and the interface piece (Figure B-1). This determines the O.A. misalignment due to the fixed clamp.

(d) The angle (in the horizontal plane) between the mirrored surfaces of the interface piece and the side of the sensor. This determines the O.A. misalignment due to the adjustable clamp.

From these measurements, the total sensor misalignment (angle between the sensor axes and IMU block) can be easily found by vectorial addition of the appropriate angles. However, since the purpose of the tests is to study the behavior of the fixed and adjustable clamps individually and determine the capabilities and limitations of each, the total sensor misalignment need not be calculated, except for an estimate of the total error.

Since the angular misalignment will be extremely small (typically, a few arc secs for the I.A.), the I.A. measurement accuracy will have to be on the order of 0.1 arc sec. O.A. measurements should be accurate to within an arc second. These accuracy requirements can easily be met

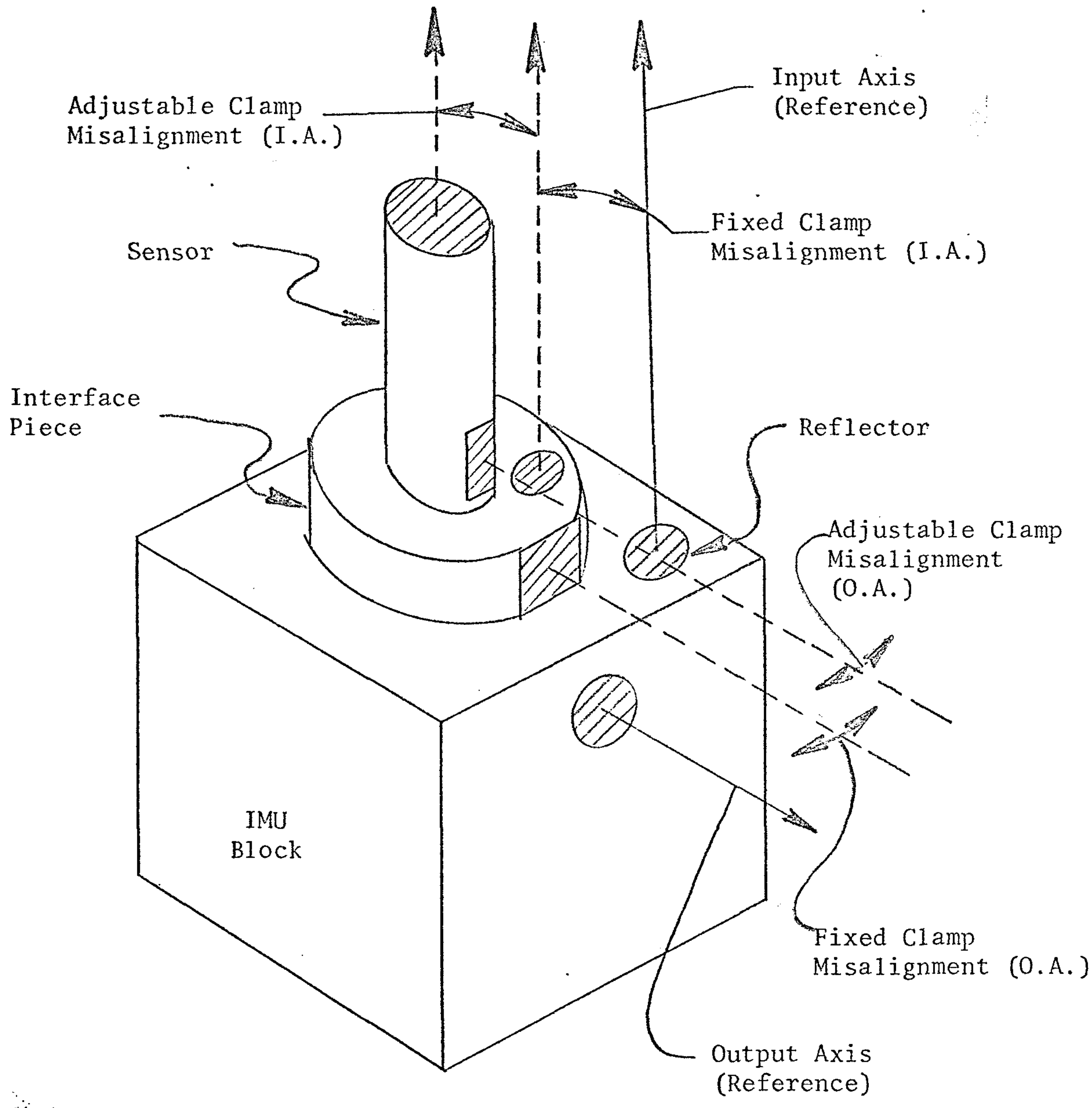

Figure B-1. Basic Parts of Test Unit

by collimation. Reflecting surfaces are provided for this purpose on the IMU block, interface piece and sensor by which the appropriate angles can be determined. The measurement of the angle between any pair of reflectors is performed by simultaneous sighting (aperture sharing) with the autocollimator.

In addition to the accuracy requirements specified above, the autocollimator chosen must also have a sufficiently large aperture to permit the sighting of both reflectors. The measuring instrument requirements for each test are set down in the following sections*.

A view of the test prototype as seen from above is shown in Figure B-2a. The I.A. reflecting surfaces of the IMU block, interface piece and sensor are indicated. Also shown are the positions in which the autocollimator beam should be made incident on the unit, in order to measure the I.A. misalignment. In Position 1a, the beam is made incident on the IMU block and interface piece reflecting surfaces, thus measuring the angular error of the fixed clamp. In Position 2a, the beam is made incident on the interface piece and sensor reflectors, thereby measuring the angular error of the adjustable clamp. In some cases (e.g. pre-alignment) it will be desirable to measure directly the total misalignment of the sensor I.A. rather than obtain it by (vectorial) addition of the fixed and adjustable clamp misalignment. For such a measurement, the beam must be oriented as shown in Position 3a.

The O.A. reflecting surfaces are shown in Figure B-2b. The required O.A. measurements can be made by orienting the autocollimator beam in Positions 1b and 2b. The former gives the O.A. error due to the fixed clamp while the latter gives the error due to the adjustable clamp. Because of the close spacing of the three O.A. reflectors, it may be necessary to mask one of them if it is found to interfere with the measurements taken while sighting the other two.

The test plan has been drawn up in conformity with the guidelines given in Appendix A. In conducting the tests, it is desirable to perform the less severe ones first, so that, if the unit is damaged accidentally in the later stages of testing, the earlier data will be available to help in the design of an improved assembly.

The tests that are needed to evaluate the alignment capability of the unit under different environmental conditions are given in Table B-1. The are listed in the order in which they should be performed.

Details of the tests, describing the procedure and the equipment required, are presented in the section that follows.

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*For reasons of economy and convenience, wherever possible, the tests were designed around instruments that were available at NASA-ERC.

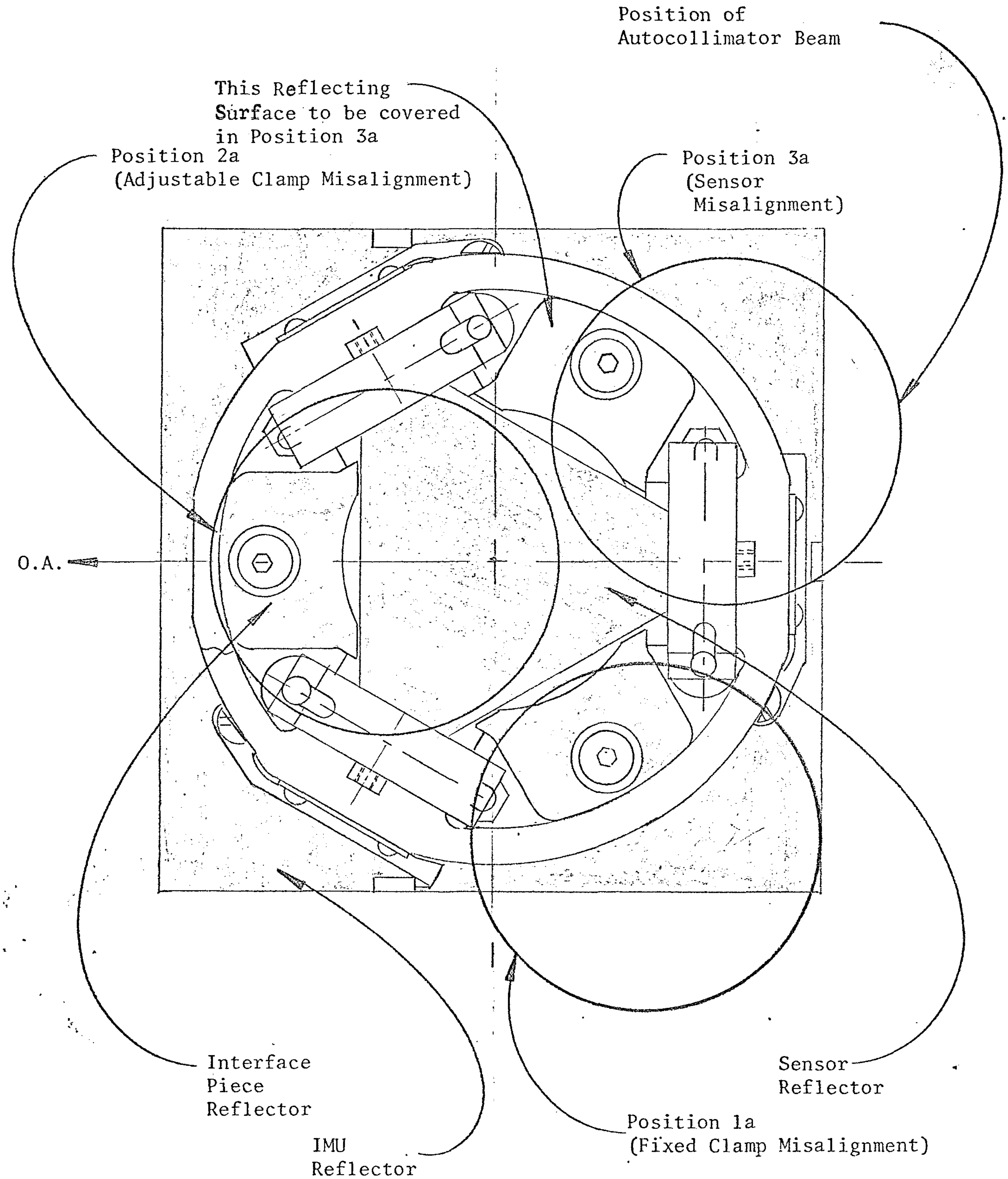


Figure B-2a. Top View of Assembly showing I.A. Reflectors

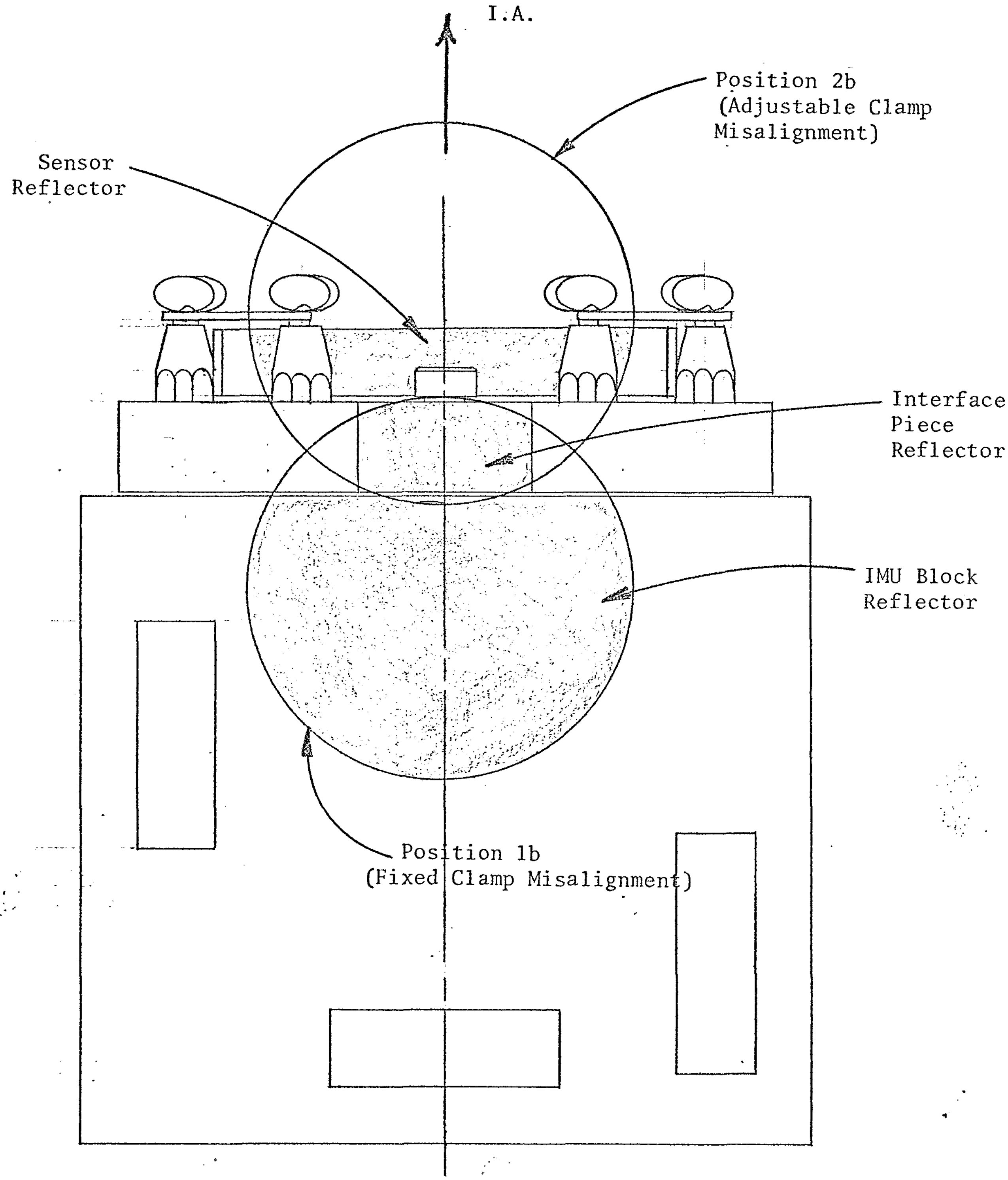


Figure B-2b. Side View of Assembly showing O.A. reflectors

Test Description	No. of Tests	Remarks
1. Pre-Alignment 1a I.A. Alignment 1b O.A. Alignment	 1 1 2	Alignment check and Deflection under 2g load
2. Repeatability	1	1 clamping cycle
3. Thermal Loading 3a Temperature Cycling 3b Steady Temperature Gradients 3c Unsteady Temperature Gradients 3d Heating in Vacuum	 2 4 4 2 12	Steady Gradients
4. Repeatability and Stability	1	4 clamping cycles over 12 hours
5. Acceleration	2	Along two orthogonal axes
6. Acoustic Excitation 6a Single Tone 6b Random	 1 1 2	
7. Vibration 7a Sinusoidal 7b Random	 2 2 4	Along two orthogonal axes
8. Shock Load	3	Along three orthogonal axes
Total number of tests	27	

Table B-1. Test Plan

Test Details

Test 1: Pre-alignment

When the test prototype is assembled initially, it will be out of adjustment. Before proceeding to the environmental testing, it is necessary to align the unit. Alignment of the I.A. is carried out by means of three adjustment screws. These adjustment screws shown schematically in Figure B-3 - form the three legs of an equilateral tripod support. Rotation of any one screw causes the sensor I.A. to move in a plane normal to the opposite side of the tripod support points.

Output axis alignment is established by means of rigid stops, hence O.A. pre-alignment is automatic, and no adjustment is required.

The pre-alignment procedure thus consists of

(a) Aligning the sensor I.A. along the IMU block reference.

(b) Checking the alignment of the O.A.

These tests are described in the following sections.

Test 1a: Input Axis Pre-alignment

Instrumentation: One Autocollimator
Two Axis, visual readout
Range: 1 arc min.
Accuracy: 0.1 arc sec.
Aperture: 2 1/2 in. dia.
(Davidson Optronics Model D-656)

Test Equipment: Clamp Assembly
Surface Plate

Procedure: The unit is placed on the surface plate with the O.A. vertical (Figure B-4). The autocollimator is also placed on the plate, about 3' to 5' away from the unit, with the optical axis along the sensor I.A. The beam is made incident on the unit as shown in Position 3a, Figure B-2a.

The initial I.A. error is then determined by simultaneous sighting of the two reflecting surfaces. In general, this error will have a component both in the horizontal and vertical planes. Firstly, the error in the horizontal plane is removed by turning the adjustment screw (2) or (3). Then the error in the vertical plane is removed by turning adjustment screw (1)*. As with any physical unit, there is likely

*If, due to this adjustment, an error in the horizontal plane reappears, the process can be repeated and the resultant error will converge to zero.

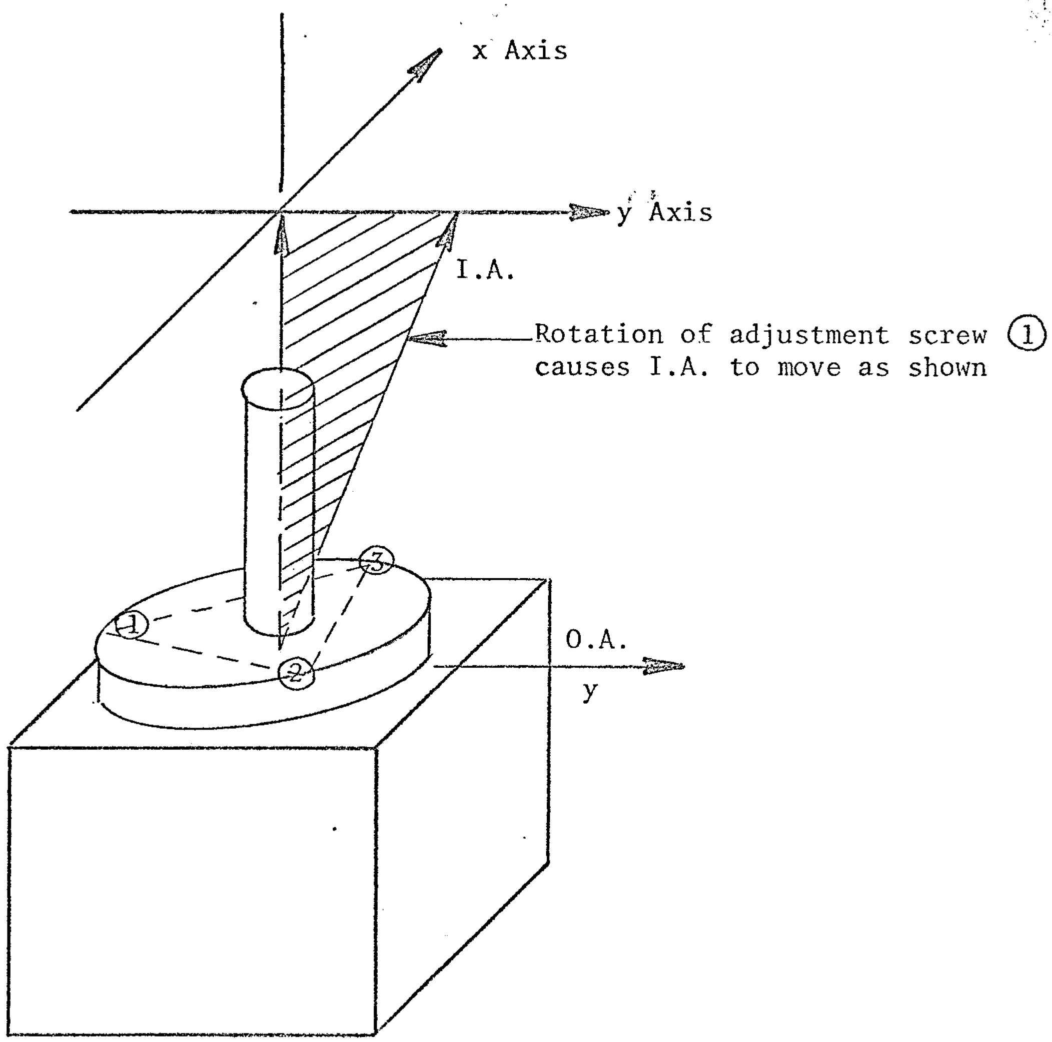


Figure B-3. Schematic Diagram of Adjustable Clamp

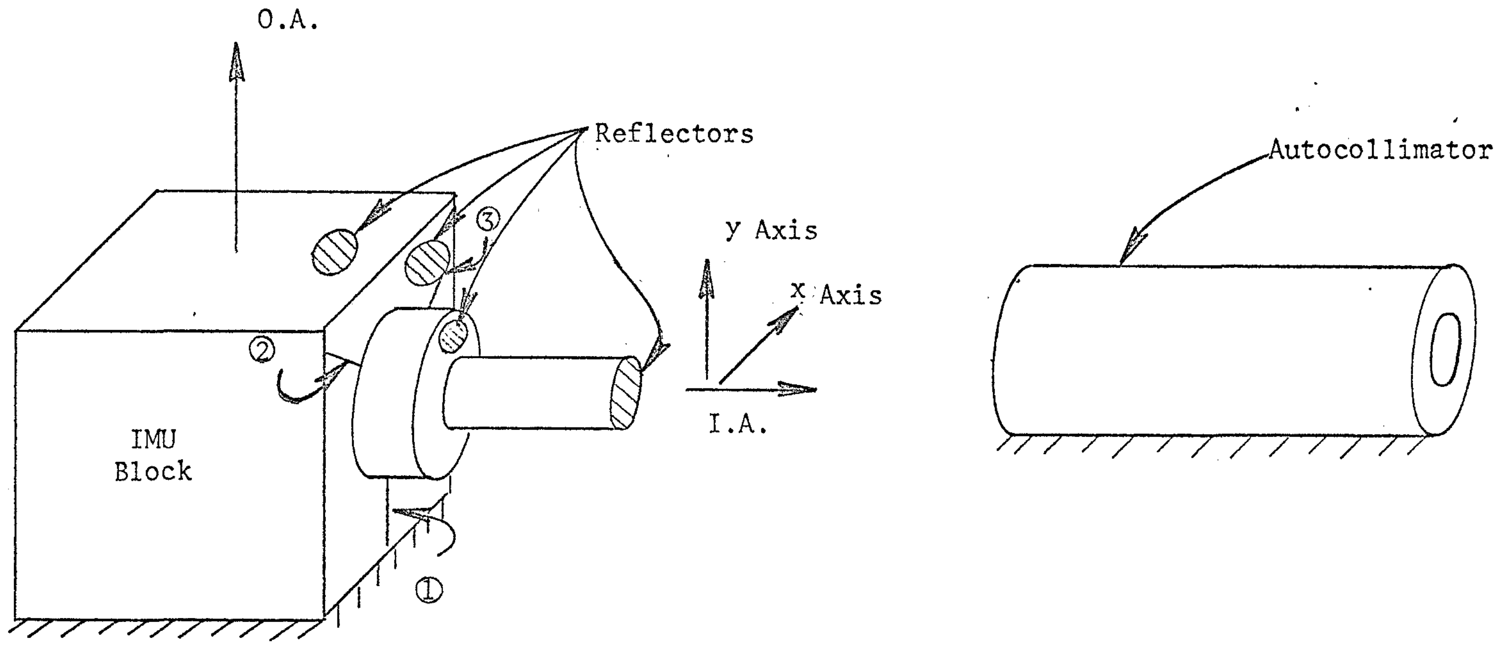


Figure B-4. Input Axis Alignment Procedure to be some small angular error (due to clearance, friction, etc.) which cannot be removed. This error must be recorded.

In this test, the weight of the assembly causes a 1g transverse load to act on the clamps. If the sensor operates with the I.A. vertical, or in a zero g environment, the alignment may be affected. The deflection due to gravity must now be determined, and an appropriate correction made. This can be carried out by rotating the unit 180 degrees about the horizontal axis (so that the O.A. is inverted) and measuring the I.A. error as before. Since the direction of gravity (relative to the unit) has been reversed, the angular change represents the deflection under a 2g load.* With the unit in this position, adjustment screw (1) can be rotated to remove half this error. The sensor I.A. has now been aligned, and transverse loading effects have been compensated for.

As a check of the above measurements, and to determine the alignment of the individual clamping units (fixed and adjustable), it is now necessary to measure the angular alignment of the fixed and adjustable clamps individually. The procedure is very similar to that described above. The unit and autocollimator are positioned as before (Figure B-4). The appropriate reflectors are then sighted and the angular misalignment measured (Position 1a for fixed clamp and Position 2a for adjustable clamp). The unit is rotated through 180 degrees and the measurements repeated. In this way, the mean angular error of the fixed and adjustable clamps can be found.

Since readings with a standard autocollimator are generally taken along two orthogonal axes, it is convenient to define a set of coordinate directions to facilitate interpretation of the data. The x and y axes along which the angular measurements should be taken are shown in Figures B-3 and B-4. Thus each angular measurement will be recorded in terms of its x and y components, and from these, the magnitude and direction of the error can be found.

Results: The following results will be obtained from the above test:

(i) Adjustable Clamp

(a) Resolution
(b) Angular Deflection under 2g transverse load

(ii) Fixed Clamp

(a) Alignment error
(b) Angular Deflection under 2g transverse load

*Assuming that the force-deflection characteristic is linear for the small deflections that are under consideration.

In addition to the above results, the deflection measurements will be extrapolated to give the deflection of the fixed and adjustable clamps under a 3g load. The readings taken during this test should be recorded in Table B-2. The data can then be reduced to give the required results.

Test 1b: Output Axis Alignment Check

Instrumentation: One Comparative Autocollimator
Single Axis, visual readout
Range: 2 arc min.
Accuracy: 1 arc sec.
Aperture: 2 1/2 in. dia.
(Davidson Optronics Model D-600)

Test Equipment: Clamp Assembly
Surface Plate

Procedure: The alignment of the O.A. must now be checked. The unit is placed on the surface plate with the sensor vertical (Figure B-5). The autocollimator is placed as shown and oriented to sight the O.A. reflectors. Since O.A. misalignment is measured in the horizontal plane, a single-axis comparative autocollimator is particularly well suited for making the measurement. The positive direction is defined as a clockwise rotation of the axis in question (with respect to the IMU block O.A.), as shown in Figure B-5.

At first, the autocollimator is used to sight the IMU block and interface piece reflectors (Position 1b, Figure B-2b), and from this, the fixed clamp angular error can be determined. Then, the interface piece and sensor reflectors are sighted (Position 2b, Figure B-2b), thereby giving the O.A. angular error due to the adjustable clamp. The angular orientation of the sensor with respect to the IMU block reference can be found from the sum of the above two readings.

Results: The following results will be obtained:

(i) Misalignment of sensor O.A.
(ii) O.A. error due to fixed clamp.
(iii) O.A. error due to adjustable clamp.

The readings of this test can also be recorded in Table B-2.

The basic measurement process described above will be repeated in many of the remaining tests. The I.A. error is measured twice (with gravity acting in opposite directions relative to the unit) for the fixed and adjustable clamps individually. The true misalignment is then given

		Input Axis Alignment				Output Axis Alignment
		O.A. Upright		O.A. Inverted		
		x Component	y Component	x Component	y Component	
1	Sensor Misalignment					X
2	Fixed Clamp Misalignment					
3	Adjustable Clamp Misalignment					

(All readings in arc secs)

Table B-2. Pre-alignment Test

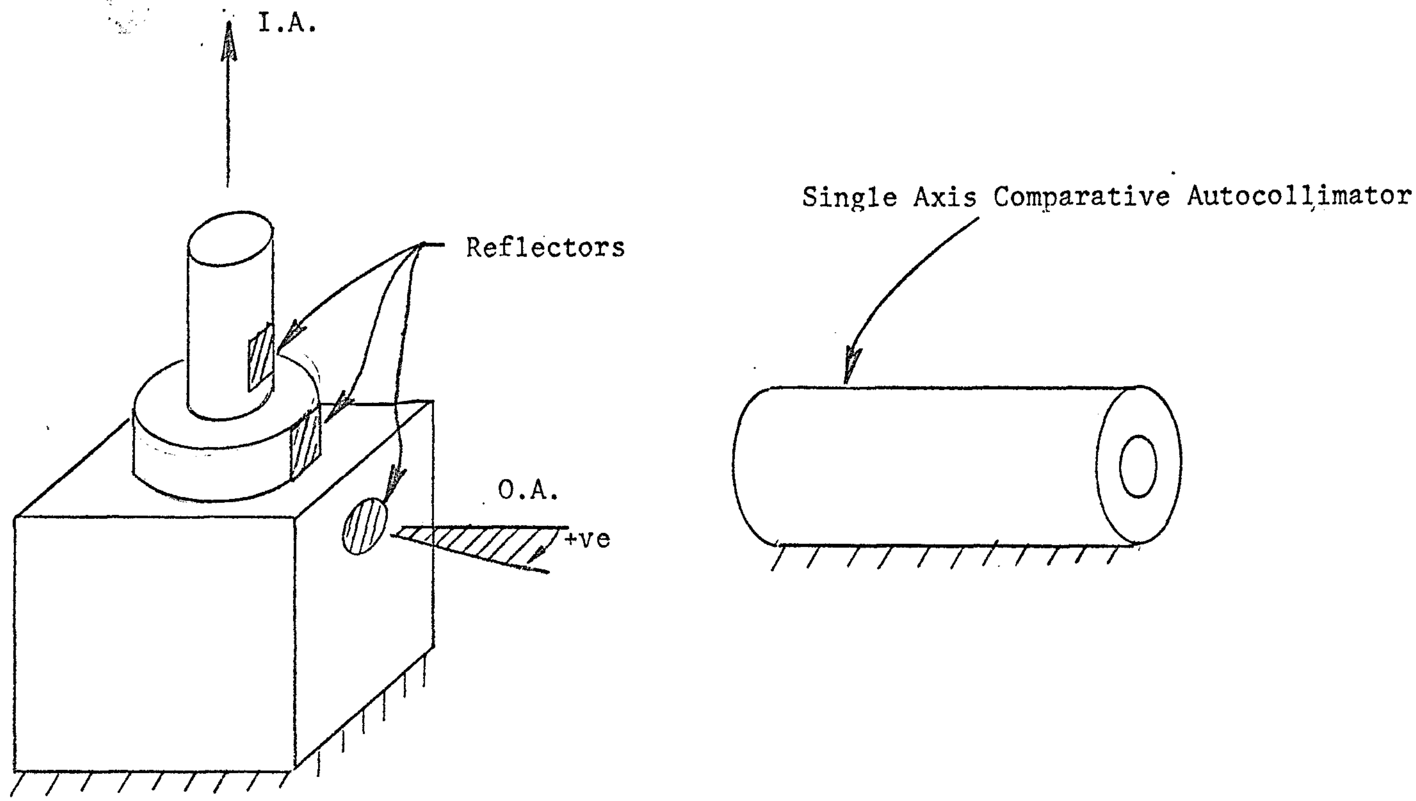


Figure B-5. Output Axis Alignment Check

by the mean of the two measurements. The O.A. error is measured with the sensor vertical. The misalignment due to the fixed and adjustable clamps can then be determined separately.

At the beginning of every test, it will be necessary to realign the sensor I.A. (as described in Test 1a), particularly if, as a result of the previous tests, the total I.A. error exceeds 3 arc secs.

Test 2: Repeatability

Instrumentation: Same as Test 1

Test Equipment: Same as Test 1

Procedure: The function of the clamp is to allow the sensor to be replaced in the field without need for alignment. Therefore, the alignment of the clamp surfaces after a number of clamping cycles must be measured. Initially, a simple repeatability test of one clamping cycle is undertaken. Later, a more severe repeatability (and short-term stability) test will be described.

Since clamping and unclamping occurs at the fixed clamp interface, it is only necessary to measure the alignment of the fixed clamp. The angular alignment of the fixed clamp is determined by measuring the angle between the IMU block and interface piece reflectors. Two sets of measurements must be made - one for the I.A. (Figure B-4) and one for the O.A. (Figure B-5). The measurement procedure is described in Test 1.

The assembly is now unclamped and then clamped back on again. The measurement process is repeated. From these readings, the angular error introduced due to the clamping cycle can be found.

Results: The following results will be obtained:

Fixed Clamp:

(i) Change in I.A. alignment after clamping cycle.
(ii) Change in O.A. alignment after clamping cycle.

The readings taken during the test can be entered in Table B-3.

Test 3: Thermal Loading: When the inertial sensing unit is in operation, the clamps will be subjected to various types of heat loads. These will arise from heat generation within the sensor and heat dissipation from neighboring units. Although the sensor and IMU block are designed to operate efficiently in a constant temperature environment (generally 150 degrees F), nevertheless, malfunction of the temperature control system will lead to a change in the ambient temperature. Thus, in addition to thermal gradients, temperature cycling tests will also have to be performed.

	Fixed Clamp Misalignment					
	Input Axis				Output Axis	
	O.A. Upright		O.A. Inverted			
	x Component	y Component	x Component	y Component		
1						Initial Reading
2						After Clamping Cycle

(All readings in arc secs)

Table B-3. Repeatability Test (1 clamping cycle)

Temperature gradients are established by means of (electrical) heating elements placed within the IMU block and sensor. There are three cartridge heaters within the IMU block and one within the sensor. The heaters can be combined to provide symmetrical* as well as asymmetrical heat inputs. Their locations are shown in Figure B-6.

Temperature gradients will be estimated by means of temperature differences measured at specific points on the clamp assembly. Such measurements are made by thermocouples, potted into the clamp assembly at the nine locations shown in Figure B-6. As can be seen, three thermocouples (a, b and c) are placed at each of the three support locations (1, 2 and 3) of the clamp assembly. The temperature change across (a) and (b) gives the temperature difference across the fixed clamp interface, while the difference between (b) and (c) gives the temperature difference across the adjustable clamp interface. The symmetry or asymmetry of the heat loading can be found by comparing the corresponding temperatures at locations (1), (2) and (3).

The heaters can be operated either symmetrically or asymmetrically, so as to produce a symmetric or an asymmetric temperature gradient. A symmetric temperature gradient is one where the temperatures at the three support points of the IMU block (and sensor) are equal.

Thus denoting the temperature at location (1a) by T(1a), a symmetrical gradient requires

$T(1a) = T(2a) = T(3a)$
and $T(1c) = T(2c) = T(3c)$

For an asymmetric gradient, the above equalities do not hold.

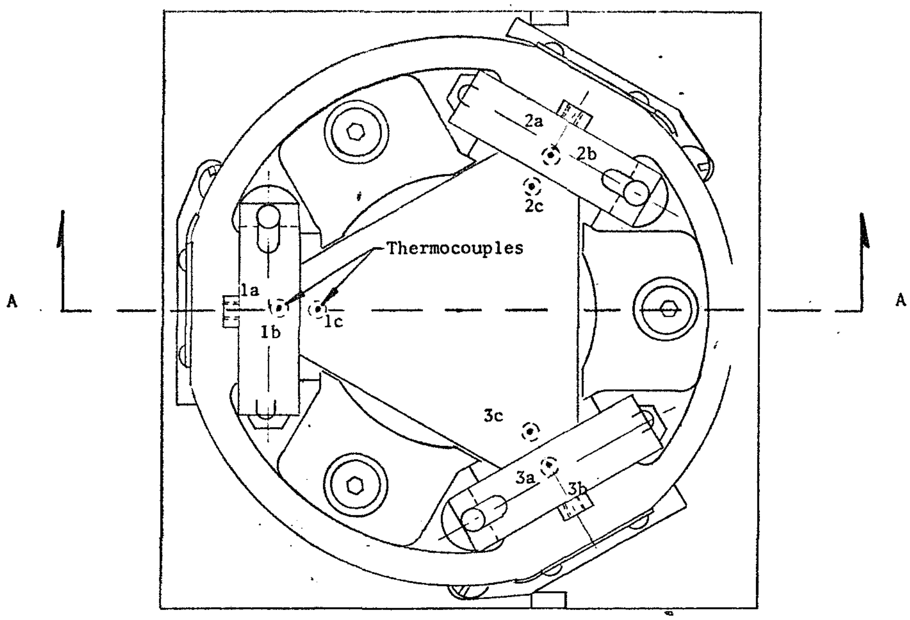
The tests that should be performed to determine the clamp behavior under heat load are given below:

(1) Ambient Temperature Cycling
(2) Temperature Gradients within Clamp Assembly
(3) Thermal loading in vacuum.

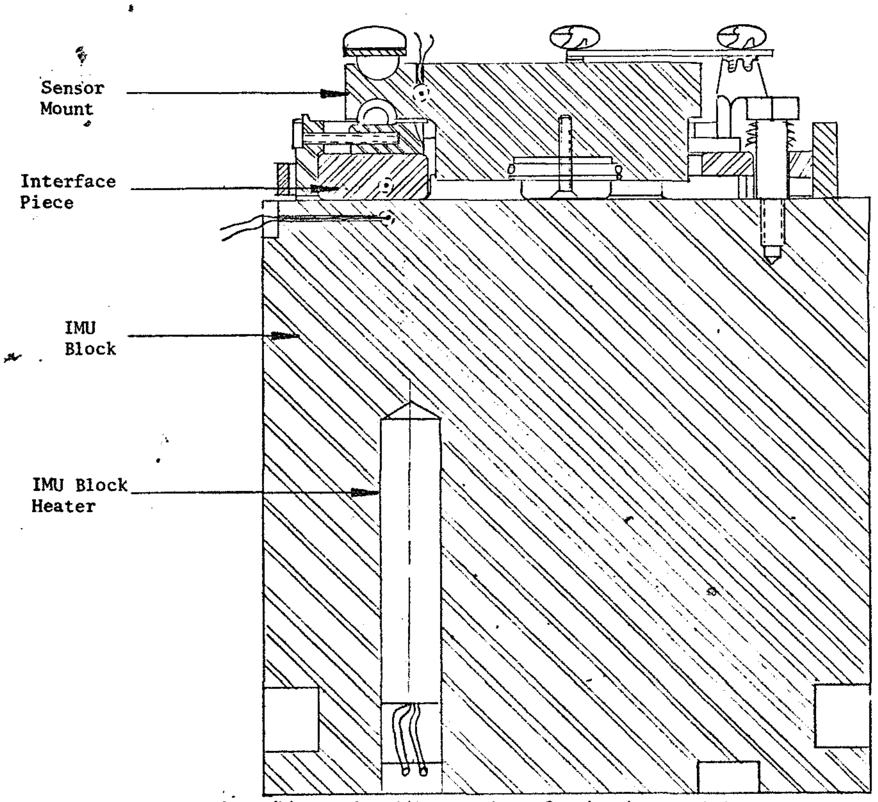
Test 3a: Ambient Temperature Cycling

Instrumentation: Same at Test 1

*With respect to the Input Axis.



(a) Top view of Unit



(b) Sectional Front view of Unit through A-A

Figure B-6. Diagram of Test Unit showing Thermocouples

Test Equipment: Test Unit

Environmental Test Chamber
Internal dimensions about
1 1/2' x 1' x 1', with an observation window through which the mirrors can be sighted.

Temperature: Ability to cycle ambient temperature between 0 degrees F and 180 degrees F within a period of half an hour.

Pressure: Ability to provide normal (1 atm) and reduced pressure (10^{-5} Tor.) environment during temperature cycling.

Strip-Chart Recorder (10 channel)

Procedure: The basic test procedure consists of placing the unit in the environmental chamber,and measuring the alignment of the clamp axes periodically during the ambient temperature cycling. Since there are four angular measurements that must be made (see Test 1), it will be found to be convenient to perform the test twice. In the first test, the I.A. alignment (fixed and adjustable clamps) can be measured, while in the second test, the O.A. alignment can be observed.

The first test is conducted with the sensor horizontal, and the autocollimator set up as shown in Figure B-7 to observe the appropriate I.A. reflectors. The ambient temperature cycling (0 degrees F to 180 degrees F, 2 cycles/hr.) is begun. Since the temperature will cycle every 1/2 hr, readings of I.A. alignment for the fixed and adjustable clamps should be taken every 5 minutes. In addition, the ambient temperature within the chamber, and the (nine) thermocouple readings must be recorded continuously. This can be done with the help of a suitable strip-chart recorder. This test should be conducted over a one hour period, in which time the ambient temperature will have completed two cycles. The readings, however, must be continued till two successive measurements differ by less than 0.1 arc sec. The data can be entered in Table B-4a.

For the second test, the unit is placed inside the environmental chamber with the sensor vertical. The autocollimator is positioned so as to sight the appropriate O.A. reflectors. A sketch of the arrangement is shown in Figure B-8. After the temperature cycling is begun, the readings are taken as before - at intervals of five minutes each. The data can be entered in Table B-4b.

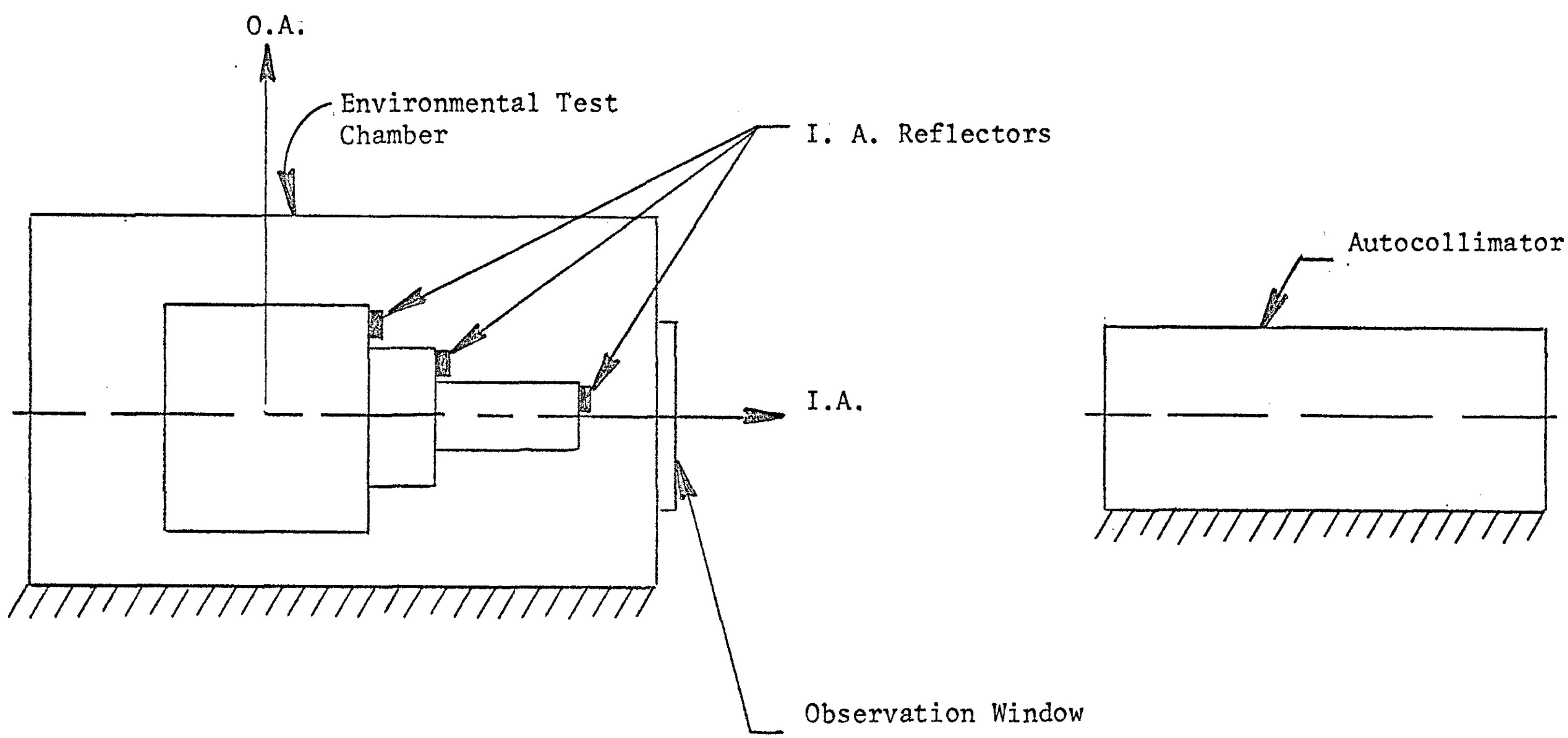


Figure B-7. I.A. Alignment Measurement During Temperature Cycling

Time from Start (Min)	No.	Fixed Clamp Alignment		Adjustable Clamp Alignment		
		x Component	y Component	x Component	y Component	
Start 0	1					Start of Temperature Cycling
5	2					
10	3					
15	4					Readings of Angular Error every 5 min. during Temperature Cycling
20	5					
25	6					
30	7					
35	8					
40	9					
45	10					
50	11					
55	12					
60	13					End of Temperature Cycling
65	14					
70	15					
75	16					Reading every 5 min. until error variation less than 0.1 arc sec
80	17					
85	18					
90	19					

(All readings in arc secs)

Table B-4a. Ambient Temperature Cycling Test (Input Axis Alignment)

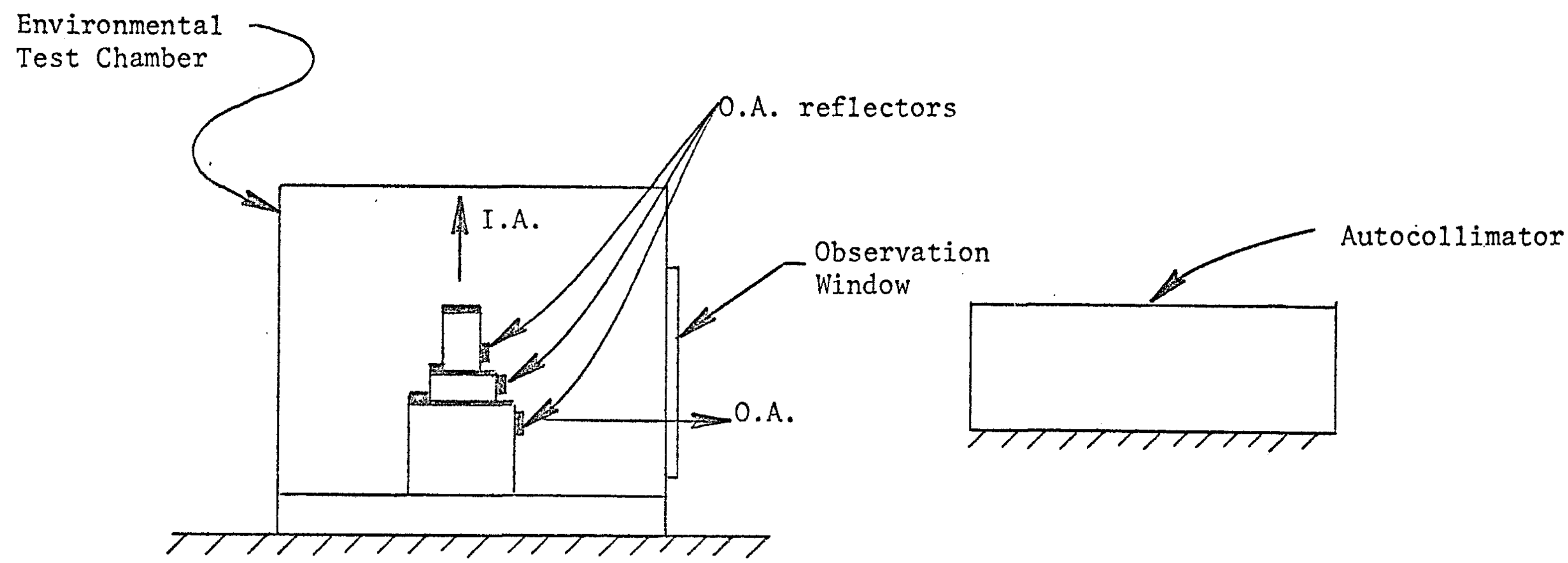


Figure B-8. O. A. Alignment Measurement During Temperature Cycling

Time from start (Min)	No.	Fixed Clamp Alignment	Adjustable Clamp Alignment	
Start 0	1			Start of Temperature Cycling
5	2			
10	3			
15	4			
20	5			Readings of Angular Error every 5 min. during Temperature Cycling
25	6			
30	7			
35	8			
40	9			
45	10			
50	11			
55	12			
60	13			End of Temperature Cycling
65	14			
70	15			
75	16			
80	17			Reading every 5 min. until error variation less than 0.1 arc sec
85	18			
90	19			

(All readings in arc secs)

Table B-4b. Ambient Temperature Cycling Test (Output Axis Alignment)

Results: The data taken during the temperature cycling test will indicate whether there is any shift in the clamp axes due to variations in the ambient temperature. Such a shift could occur due to nonsymmetrical heat conduction. The data will be reduced to give the I.A. and O.A. shift of the clamp assembly and determine if the errors are periodic and disappear after the cycle is completed or whether a permanent shift in alignment occurs.

Test 3b: Steady Thermal Gradients

Instrumentation: Same as Test 1

Test Equipment: Clamp Assembly
Surface Plate
Temperature Controller and Readout

Procedure: (i) Small Gradients

The alignment of the clamp surfaces is to be checked while there is a temperature gradient across the clamp components. The alignment of the clamp surfaces (I.A. and O.A.) is measured initially, as before. Heating of the unit is then begun. After the specified temperature differences have been established (in the steady state), the alignment is measured again. From these two sets of readings, the angular error introduced due to the temperature gradients will be found. All ten thermocouple temperatures must also be recorded. Finally, as an added check, the alignment is measured again after the unit has cooled down to room temperature. It is desirable to obtain this alignment error for symmetrical as well as asymmetrical temperature gradients. This can be done by performing three tests, with the following temperature specifications:

(1) Symmetrical Heating of sensor

$T(1c) - T(1a) \simeq 1/4$ degrees F

(2) Asymmetrical Heating of sensor

$T(1c) - T(2c) \simeq T(1c) - T(3c) \simeq 3/4$ degrees F

(3) Asymmetrical Heating of IMU Block

$T(1a) - T(2a) \simeq T(1a) - T(3a) \simeq 3/4$ degrees F

The data taken during this test can be entered in Table B-5a.

(ii) Moderate Gradients

When the unit is subjected to larger gradients than those described in (i) above, the misalignment will become larger. In such cases, it is desirable to determine whether the clamps return to alignment after the gradients have been removed. Thus in this test, the procedure consists of measuring the initial alignment, subjecting the unit to the required temperature gradients, allowing the unit to cool to room temperature, and measuring the alignment again. In this manner, the permanent error introduced due to the (temporary) thermal gradient can be found by comparing the initial and final readings. The nine thermocouple readings must also be recorded.

The initial alignment measurement can be carried out as before. Heating of the IMU block is then begun so as to establish the following temperature differences:

$$T(1a) - T(2a) \simeq T(1a) - T(3a) \simeq 3 \text{ degrees F}$$

After the steady state is reached, the heating must be continued to maintain the temperature gradients for four hours. The unit is then allowed to cool down to room temperature and the clamp alignment is measured again. While the unit is being heated, it should be placed on its side with the O.A. vertical. In this position, the sensor weight tends to increase the I.A. misalignment and thus represents the most severe case of gravity loading on the unit. The data obtained during the test can be entered in Table B-5b.

Results: (i) Small Gradients

The ability of the clamp to remain in alignment when subjected to small temperature gradients will be established. The data will be reduced to give the angular errors introduced in the I.A. and O.A. alignment under the specified temperature variation. The results will be obtained individually for the fixed and adjustable clamps, and will include results for symmetrical and asymmetrical gradients.

(ii) Moderate Gradients

As the temperature gradients (asymmetric) increase, the clamp misalignment will become larger. For such cases, the clamp alignment will be checked before and after the unit is heated. From the data obtained, the permanent shift in the I.A. and O.A. following the heating and cooling of the unit will be determined. The results will be obtained for the fixed and adjustable clamps individually.

		Fixed Clamp Alignment					Adjustable Clamp Alignment						Sensor Support Temperatures (°F)	Interface Piece Temperatures (°F)	IMU Block Temperatures (°F)
		Input Axis				Output Axis	Input Axis				Output Axis				
		O.A. Upright		O.A. Inverted			O.A. Upright		O.A. Inverted						
		x Component	y Component	x Component	x Component		x Component	y Component	x Component	y Component					
Symmetrical Heating of Sensor	1											Initial Reading (Room Temperature)	T(1a)= T(2a)= T(3a)=	T(1b)= T(2b)= T(3b)=	T(1c)= T(2c)= T(3c)=
	2											During Specified Symmetrical temperature gradient			
	3											Final Reading (Room Temperature)			
Asymmetrical Heating of Sensor	1											Initial Reading (Room Temperature)	T(1a)= T(2a)= T(3a)=	T(1b)= T(2b)= T(3b)=	T(1c)= T(2c)= T(3c)=
	2											During specified Asymmetrical temperature gradient			
	3											Final Reading (Room Temperature)			
Asymmetrical Heating of IMU Block	1											Initial Reading (Room Temperature)	T(1a)= T(2a)= T(3a)=	T(1b)= T(2b)= T(3b)=	T(1c)= T(2c)= T(3c)=
	2											During Specified Symmetrical temperature gradient			
	3											Final Reading (Room Temperature)			

(All readings in arc secs)

Table B-5a. Small Temperature Gradient Test

	Fixed Clamp Alignment					Adjustable Clamp Alignment					
	Input Axis				Output Axis	Input Axis				Output Axis	
	O.A. Upright		O.A. Inverted			O.A. Upright		O.A. Inverted			
	x Component	y Component	x Component	y Component		x Component	y Component	x Component	y Component		
1											Initial Reading (Before Heating)
2											Final Reading (After Heating)

(All readings in arc secs)

Sensor Support Temperatures (°F)	Interface Piece Temperatures (°F)	IMU Block Temperatures (°F)
T(1a) =	T(1b) =	T(1c) =
T(2a) =	T(2b) =	T(2c) =
T(3a) =	T(3b) =	T(3c) =

Table B-5b. Moderate Temperature Gradient Test

Test 3c: Unsteady Thermal Gradients

The clamping unit should be tested under steady as well as unsteady thermal conditions. During the unsteady state tests, the clamp alignment may change rapidly and hence visual observation and recording will not be convenient. Hence the angular error must be measured and recorded automatically (by electronic means, for instance).

A standard automatic autocollimator (photoelectric readout) can be used to determine the angular orientation of a single mirror (with respect to the instrument reference axis). To determine the angle between two mirrors, a shutter assembly is required, so as to direct the autocollimator beam first onto one mirror, and then onto the second and so on in quick succession. In this manner, an intermittent reading on both mirrors can be obtained, and from this the angle between them determined. In order to obtain accurate results, the switching frequency or sampling rate must be substantially higher than the frequency of the angular variations to be measured.

The unsteady gradients will last for a period of about 30 seconds (frequency of interest about 1/30 hz), so that the sampling rate should be about once every 3 secs or quicker. Usually, the photoelectric readout on an automatic autocollimator has a response time of about 1 sec, so the required shuttering rate can be once every two seconds or so. A typical readout during the unsteady tests is shown in Figure B-9.

Instrumentation: Autocollimator

Two axis, photoelectric readout
Range: 1 arc min
Accuracy: 0.1 arc sec
Aperture: 2 1/2 in. dia.
(Davidson Optronics Model D-707)

Shutter Assembly

Capable of continuous operation at about 1/4 hz.
(Davidson Optronics Model D-570)

Strip Chart Recorder (10 channel)

Test Equipment: Clamp Assembly
Temperature Controller and Readout

Procedure: During the unsteady thermal tests, the unit will be heated, and then allowed to cool within a period of about 30 sec. During this time, the readings of angular error will be recorded continuously. From the results, the effects of unsteady temperature gradients on the clamp assembly will be found.

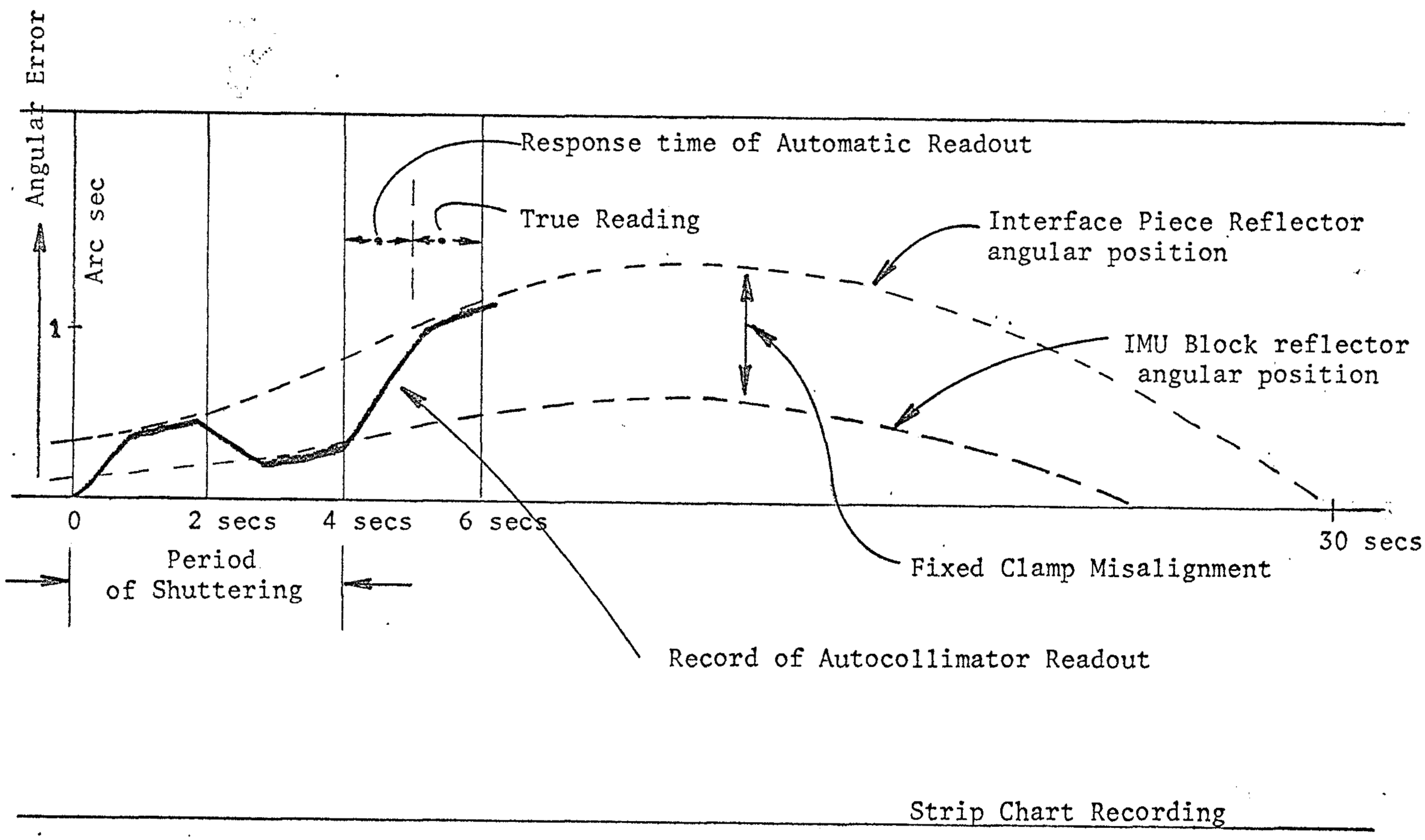


Figure B-9. Typical Readout during Unsteady Thermal Tests

The autocollimator and shutter assembly are positioned as shown in Figure B-10. When the automatic shuttering is begun, the beam is made incident on each of the two reflectors alternately, as described previously. The readings can then be recorded continuously on the strip chart recorder.

Heating of the unit will be carried out by means of the heaters and the temperature controller. When the unit is at room temperature, the heating of the sensor will be begun such that, in about 10~20 secs, the following asymmetric temperature differences are reached.

$$T(1c) - T(2c) \simeq T(1c) - T(3c) \simeq 1.5 \text{ degrees F}$$

The heaters will then be turned off and the unit allowed to cool to room temperature. During this process, the temperature of the ten thermo-couples will be recorded continuously on the strip chart recorder.

The above procedure is to be carried out four times as follows:

(i) Sensor Horizontal, Fixed Clamp I.A. Alignment (Figure B-2a, Position 1a)
(ii) Sensor Horizontal, Adjustable Clamp I.A. Alignment (Figure B-2a, Position 2a)
(iii) Sensor Vertical, Fixed Clamp O.A. Alignment (Figure B-2b, Position 1b)
(iv) Sensor Vertical, Adjustable Clamp O.A. Alignment (Figure B-2b, Position 2b)

Results: The data will be analyzed to give the change in alignment of the I.A. and O.A. of the fixed and adjustable clamps under an unsteady temperature gradient.

Test 3d: Thermal Loading in Vacuum

The clamping unit must be capable of satisfactory operation in a vacuum of 10^{-5} Tor. The main effect of this vacuum will be to change the heat transfer characteristics at the various contact inter-faces. In order to determine how this change affects sensor alignment, it is necessary to conduct some of the thermal tests in a vacuum. These tests are given below.

(i) Steady Thermal Gradients

The effects of a temperature gradient in vacuum on the alignment of the clamp surfaces must be determined. The test procedure is similar to Test 3b. However, the test will be conducted only for symmetrical temperature gradients, since, from this, the variation in contact resistance at the interfaces can be conveniently studied.

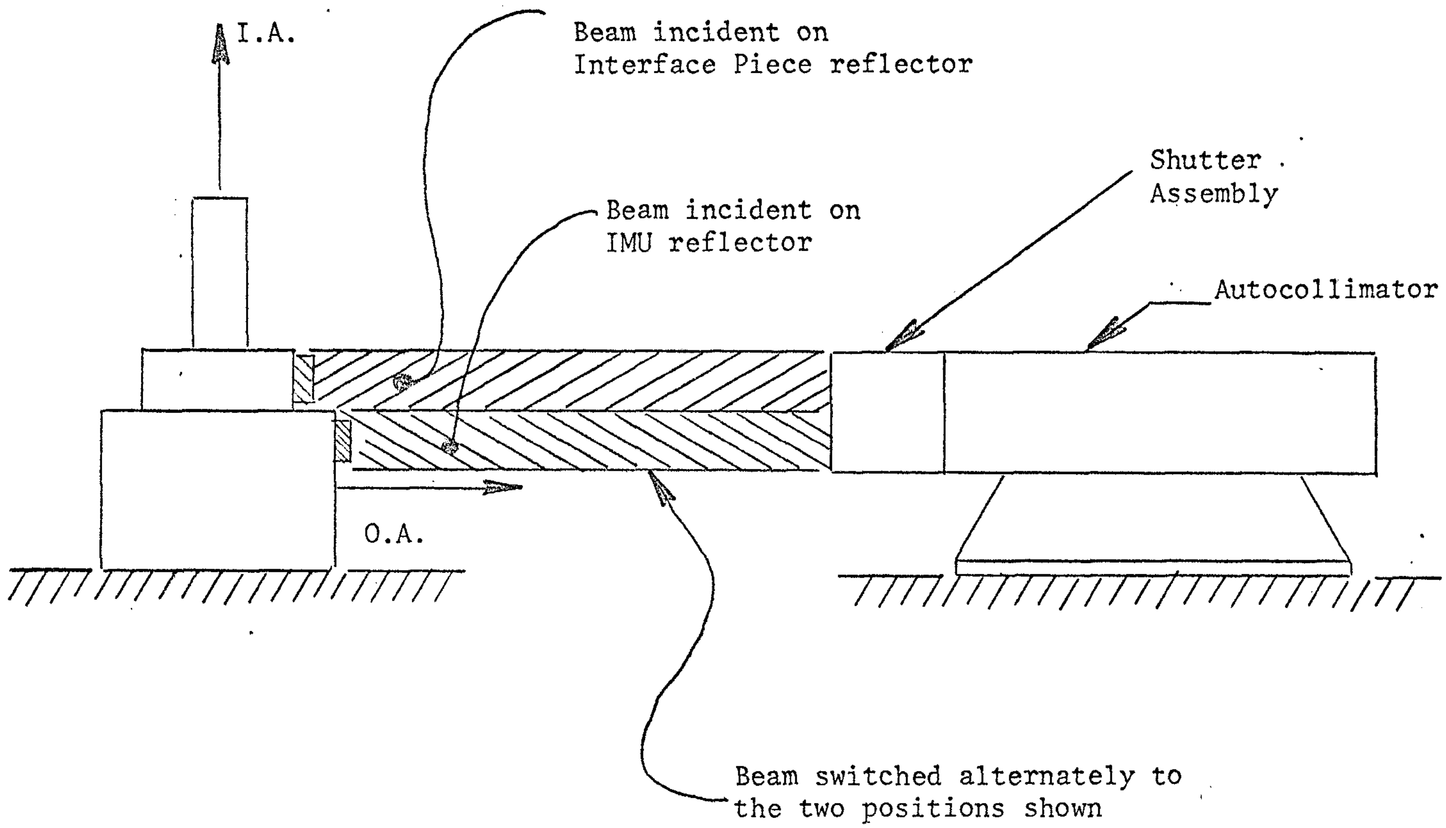


Figure B-10. Alignment Measurement during Unsteady State Thermal Tests

Instrumentation: Same at Test 1

Test Equipment: Clamp Assembly
Environmental Chamber
Temperature Controller and Readout

Procedure: The clamp is placed in the environmental chamber with the O.A. vertical (Figure B-8) and the initial alignment of the I.A. is determined. The pressure within the chamber is then reduced to 10^{-5} Tor. A second reading of I.A. alignment is then taken.

Heating of the unit is then begun. After the specified temperature differences have been established (in the steady state), the I.A. alignment is measured again. The unit is now allowed to cool to room temperature. The I.A. alignment is measured as before. The pressure within the chamber is now made equal to atmospheric pressure, and a final measurement of I.A. alignment is taken. These measurements can be recorded in Table B-6.

The above test should be carried out for a symmetrical temperature gradient:

$$T(1a) - T(1c) \cong 1/4 \text{ degree F}$$

Results: From the data, the I.A. and O.A. shift under the action of a thermal gradient in vacuum will be determined for the fixed and adjustable clamps. These results will be compared to those of Test 3b to determine how the reduced pressure environment affects the alignment capability of the unit.

Test 4: Repeatability and Stability

Instrumentation: Same as Test 1

Test Equipment: Clamp Assembly

Procedure: After the unit is pre-aligned - as described in Test 1 - the sensor is unclamped from the IMU block and then clamped back on again. When handling the unit during the clamping process, great care must be taken not to subject it to any shock loads, as these may bring about a shift in alignment, causing the results to be in error.

The angular error (I.A. and O.A.) of the fixed and adjustable clamps is measured as before. The unit is then allowed to remain undisturbed on the surface plate with the sensor horizontal, and the I.A. and O.A. alignment is measured at intervals of fifteen minutes for the first hour and then every half hour for two more hours. The removal

	Input Axis Alignment					Sensor Support Temperatures (°F)	Interface Piece Temperatures (°F)	IMU Block Temperatures (°F)
	Fixed Clamp		Adjustable Clamp					
	x Component	y Component	x Component	y Component				
1					Atmospheric Pressure Room Temperature	T (1a) =	T (1b) =	T (1c) =
2					10^{-5} Tor. Pressure Room Temperature	T (2a) -	T (2b) =	T (2c) =
3					During Symmetrical Temperature Gradient	T (3a) =	T (3b) =	T (3c) =
4					10^{-5} Tor. Pressure Room Temperature			
5					Atmospheric Pressure Room Temperature			

	Output Axis Alignment					
	Fixed Clamp	Adjustable Clamp				
1			Atmospheric Pressure Room Temperature	T (1a) =	T (1b) =	T (1c) =
2			10^{-5} Tor. Pressure Room Temperature	T (2a) =	T (2b) =	T (2c) =
3			During Symmetrical Temperature Gradient	T (3a) =	T (3b) =	T (3c) =
4			10^{-5} Tor. Pressure Room Temperature			
5			Atmospheric Pressure Room Temperature			

(All readings in arc secs)

Table B-6. Thermal Gradients in Vacuum

and insertion of the sensor is then performed as before and measurements of the I.A. and O.A. alignment are repeated. The above procedure is carried out four times.

Results: The repeatability test will be used to determine,

(a) The angular error introduced over successive clamping cycles.
(b) The short term alignment stability of the clamp assembly.

The results will be obtained for the fixed and adjustable clamps individually. The data taken during one clamping cycle can be entered in the table shown overleaf (Table B-7). For the complete test, however, four such tables will be required.

Test 5: Steady Acceleration (15 g)

Instrumentation: Same as Test 1

Test Equipment: Test Assembly
Surface Plate
Centrifuge

Procedure: The steady acceleration tests will be conducted using a centrifuge. Selection of a suitable centrifuge will depend on the ability of the machine to support the test assembly (6" x 5" x 5", 50 lbs) and subject it to a 15g acceleration for about a minute.

For an acceleration of 15g, the speed of rotation of a centrifuge can be found from the relationship

$$N = 210/\sqrt{R}$$

where N is the rotational speed in rpm and R is the radius of the rotating arm in ft.

The alignment of the fixed and adjustable clamps is initially determined as before. The test assembly is attached to the centrifuge and subjected to an acceleration of 15g for 1 minute. The unit is then removed, and the alignment of the clamp surfaces is measured again. The change in alignment of the I.A. and O.A. of the fixed and adjustable clamps can thus be determined. The 15g test should be carried out twice. First with the load acting along the I.A. (I.A. pointing radially inwards) and then with the load acting along the O.A. (O.A. pointing radially outwards). The data can be entered in Table B-8.

	Fixed Clamp Alignment					Adjustable Clamp Alignment					Time elapsed after sensor reclamping
	Input Axis				Output Axis	Input Axis				Output Axis	
	O.A. Upright		O.A. Inverted			O.A. Upright		O.A. Inverted			
	x Com- ponent	y Com- ponent	x Com- ponent	y Com- ponent		x Com- ponent	y Com- ponent	x Com- ponent	y Com- ponent		
1											Initial Reading
	Sensor unclamped and reclamped										
2											0 min.
3											15 min.
4											30 min.
5											45 min.
6											1 hr.
7											1 1/2 hrs.
8											2 hrs.
9											2 1/2 hrs.
10											3 hrs.

(All readings in arc secs)

Table B-7. Repeatability and Stability Test

		Fixed Clamp Alignment					Adjustable Clamp Alignment					
		Input Axis				Output Axis	Input Axis				Output Axis	
		O.A. Upright		O.A. Inverted			O.A. Upright		O.A. Inverted			
		x Component	y Component	x Component	y Component		x Component	y Component	x Component	y Component		
I.A. Radially Inwards	1											Initial Reading
	2											After 15g acceleration
O.A. Radially Outwards	1											Initial Reading
	2											After 15g acceleration

(All readings in arc secs)

Table B-8. 15 g Acceleration Test

Results; The observations that have been recorded in Table B-8 will be used to determine the I.A. and O.A. shift after the unit has been subjected to a short term steady acceleration of 15g. The results will be obtained for the fixed and adjustable clamps individually. The relative severity of this load acting along the two principal axes will also be determined.

Test 6: Acoustic Excitation

Instrumentation: Same as Test 1

Test Equipment: Clamp Assembly
Surface Plate
Acoustic Test Chamber

Internal dimensions about 1 1/2' x 1' x 1' and capable of providing the desired acoustic excitation (Appendix A).

Procedure: The unit is placed in the acoustic test chamber and subjected to the excitation as given in the specifications. Selection of the acoustic test facility will be based on the unit size (approximately 6" x 5" x 5"), frequency range and sound pressure levels required. The test procedure consists of measuring the fixed and adjustable clamp alignment, subjecting the unit to the prescribed acoustic excitation, and then measuring the alignment again, thereby detecting any permanent angular error caused by the acoustic disturbance. The measurement of the fixed and adjustable clamp alignment is carried out as before. After the initial measurements, the unit is placed in the test chamber with the sensor vertical. Each test condition is maintained for five minutes, following which, the unit is removed and the alignment measured again. This test will be conducted for two types of acoustic inputs.

(a) Single Tone Input

The test assembly is subjected to single tone acoustic excitation at the frequencies and pressure levels specified. Measurements of the alignment is made following each sound pressure (decibel) level. A sample form in which the readings can be entered is shown in Table B-9.

(b) Random Input

The test assembly should also be subjected to band-limited white noise (154 db rms, 37.5 - 9600 hz, Gaussian PDF) over a period of five minutes. Measurements of alignment made before and after the test will indicate the change in the alignment due to the acoustic excitation. The readings can be recorded in Table B-9.

		Fixed Clamp Alignment					Adjustable Clamp Alignment					
		Input Axis				Output Axis	Input Axis				Output Axis	
		O.A. Upright		O.A. Inverted			O.A. Upright		O.A. Inverted			
		x Component	y Component	x Component	y Component		x Component	y Component	x Component	y Component		
Single Tone Acoustic Input	1											Initial Reading
	2											After 37.5-75 hz tone
	3											After 75-150 hz tone
	4											After 150-300 hz tone
	5											After 300-600 hz tone
	6											After 600-1200 hz tone
	7											After 1200-2400 hz tone
	8											After 2400-4800 hz tone
	9											After 4800-9600 hz tone
White noise	1											Initial Reading
	2											After 37.5-9600 hz white noise

Table B-9. Acoustic Excitation Test

Results: The data obtained during this test will be processed to give the permanent angular shift of the fixed and adjustable clamps after an acoustic disturbance. Any critical frequency bands which have a significant effect on sensor alignment will be identified.

Test 7: Vibration

Instrumentation: Same as Test 1

Test Equipment: Clamp Assembly
Surface Plate
Shake Table

Capable of vibrating test unit according to the specifications (see Appendix A.)
Test Unit size 6" x 5" x 5".
weight 50 lbs.

Procedure: The vibration test will be conducted on a shake table. The amplitudes and frequencies of the sinusoidal vibration, and the power spectrum of the random input are given in Appendix A. The shake table must be capable of vibrating the test unit in accordance with these requirements.

The test consists of measuring the initial angular error of the fixed and adjustable clamps individually (both for the I.A. and the O.A.), subjecting the unit to the specified vibration, and then measuring the error again. In this way, the change in alignment after the vibration can be determined.

Since the measurements will be carried out before and after the test, and not during the vibration, the measurement procedure is the same as described in Test 1. As before, the unit is placed on the surface plate and the autocollimator used to sight the appropriate reflectors (Figures B-4 and B-5). From these readings, the angular misalignment of the fixed and adjustable clamps can be determined. The unit is then fastened onto the shake table and subjected to the specified vibration. It is removed from the shake table and placed on the surface plate, where the angular errors of the fixed and adjustable clamps are determined again.

(a) Sinusoidal Vibration

For the first set of tests - those relating to sinusoidal vibration - the alignment is measured following each test condition, i.e., after subjecting the unit to the specified vibration level over the frequency range indicated. Each test condition should be maintained for five minutes. Since the tests will be performed over four vibration levels, four sets of alignment measurements are required - one after each test condition. In addition, an initial alignment measurement must also be taken at the start of the test. These readings can be entered in the Table B-10a.

It is desirable to perform the vibration tests along two orthogonal axes of the unit. The first series of tests should be carried out with the direction of vibration along the sensor I.A., and the second series along an axis mutually perpendicular to the I.A. and O.A.

(b) Random Vibration

The next set of vibration tests to be performed are those where the vibrational excitation is band-limited white noise with a Gaussian probability density function (PDF) and the following power spectrum:

(a) $0.05g^2/hz$ 20-400 hz
(b) $0.12g^2/hz$ 400-2000 hz

Here, as before, the fixed and adjustable clamp alignment is measured before and after each test condition. The unit is then subjected to each of the two vibration levels over a period of five minutes, and the resulting misalignment due to this vibration is found. Finally the unit is subjected to an additional five minutes of random vibration having a combined spectrum of (a) and (b) above. The readings obtained during these tests can be entered in Table B-10b.

The above tests must be performed separately along two orthogonal axes of the test unit - initially with the vibration along the I.A. and then with the vibration mutually perpendicular to the I.A. and O.A.

Results: The functioning of the fixed and adjustable clamps will be studied to determine:

(i) The permanent change in I.A. and O.A. alignment after being subjected to the given vibrational load.
(ii) The critical direction along which vibrational effects cause the greatest misalignment.

Test 8: Shock Loading

Instrumentation: Same as Test 1

Test Equipment: Test Unit
Surface Plate
Impact Testing Machine

		Fixed Clamp Alignment					Adjustable Clamp Alignment					
		Input Axis				Output Axis	Input Axis				Output Axis	
		O.A. Upright		O.A. Inverted			O.A. Upright		O.A. Inverted			
		x Component	y Component	x Component	y Component		x Component	y Component	x Component	y Component		
Vibration along I.A.	1											Initial Reading
	2											After 0.5 in, 5-17 hz vibration
	3											After 7.0g, 17-22 hz vibration
	4											After 5g, 22-400 hz vibration
	5											After 7.5g, 400-3000 hz vibration
Vibration normal to I.A. and O.A.	1											Initial Reading
	2											After 0.5 in. 5-17 hz vibration
	3											After 7.0g, 17-22 hz vibration
	4											After 5g, 22-400 hz vibration
	5											After 7.5g 500-3000 hz vibration

(All readings in arc secs)

Table B-10a. Sinusoidal Vibration Test

		Fixed Clamp Alignment					Adjustable Clamp Alignment					
		Input Axis				Output Axis	Input Axis				Output Axis	
		O.A. Upright		O.A. Inverted			O.A. Upright		O.A. Inverted			
		x Component	y Component	x Component	y Component		x Component	y Component	x Component	y Component		
Vibration along I.A.	1											Initial Reading
	2											After 20-400 hz vibration
	3											After 400-2000 hz vibration
	4											After 20-2000 hz vibration
Vibration normal to I.A. and O.A.	1											Initial
	2											After 20-400 hz vibration
	3											After 400-2000 hz vibration
	4											After 20-2000 hz vibration

Table B-10b. Random Vibration Test

Procedure: The object of the shock test is to observe whether there is any change in sensor alignment after it has been subjected to the shock load. Before the test is performed, the initial alignment of the fixed and adjustable clamps is measured as described previously.

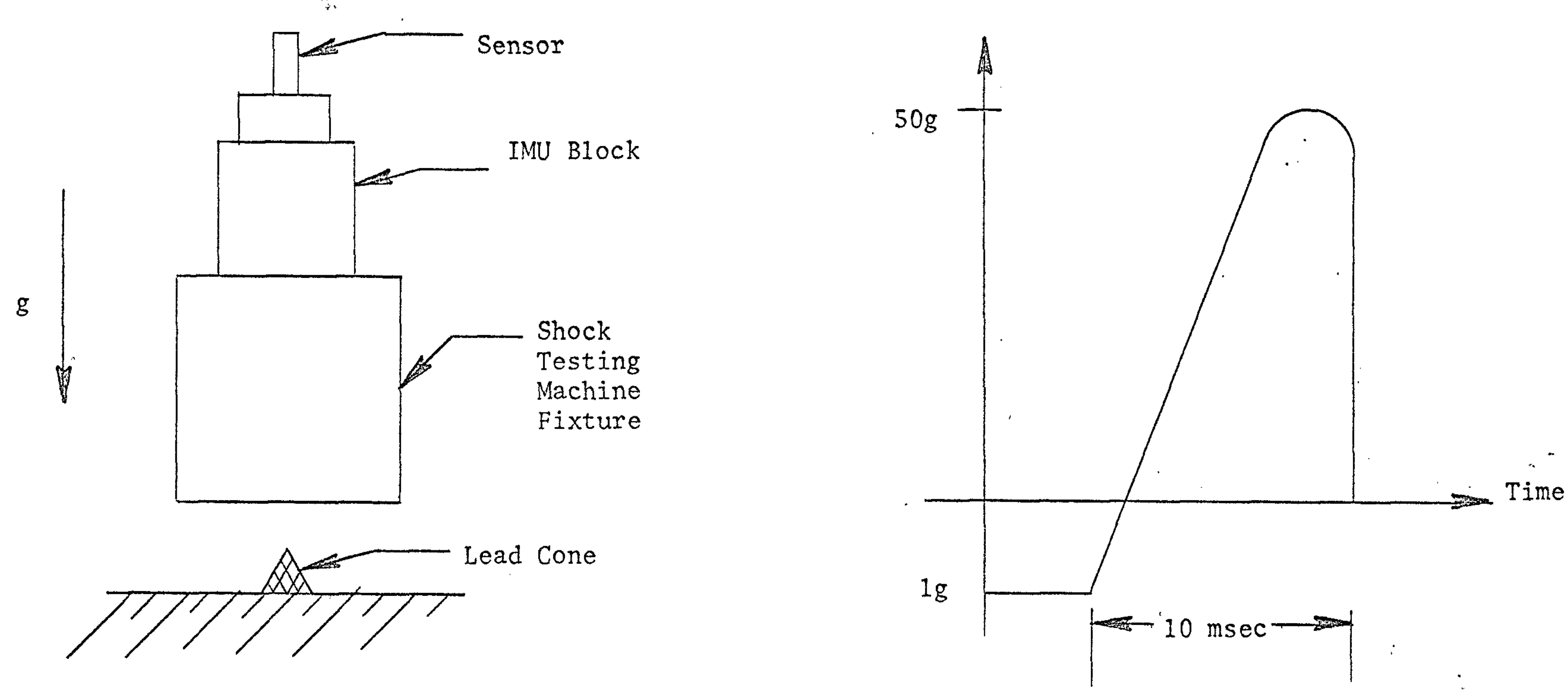
The unit is then subjected to the prescribed shock load on a shock testing machine. One form of such a machine (see Figure B-11A) consists basically of a rigid block to which the test assembly is attached. The block is allowed to fall freely over a certain distance onto a lead cone which deforms, thus providing the shock loading on the unit. For a specified loading, a suitable cone can be selected with reference to the operating manual of the machine. This type of test will apply a saw-tooth acceleration waveform to the sensor as seen in Figure B-11b. Most shock test machines operate along very similar lines and selection of a suitable facility can be made based on the unit size and weight (6" x 5" x 5", 35 lbs) and the required shock load (50 g's for 10 msec).

After the unit is subjected to the shock, the I.A. and O.A. alignment is measured again and from these and the previous measurements, the change in the alignment of the fixed and adjustable clamps due to the shock load can be found.

In order to determine the most critical direction of shock loading, the test assembly should be subjected to the shock load along three mutually perpendicular axes. Thus, the first test can be performed with the sensor vertical, while the remaining two tests should be carried out with the sensor horizontal, as shown in Figure B-12.

Results: The data from the above test will indicate the permanent angular change in clamp alignment due to the shock load. The results will be obtained for the fixed and adjustable clamps individually. The direction in which the shock loading causes the greatest misalignment will also be determined.

A table is provided overleaf (Table B-11) which the readings can be entered to facilitate subsequent reduction of the data.



(a) Schematic Diagram of Shock Testing Machine

(b) Shock Loading on Unit

Figure B-11. Shock Test

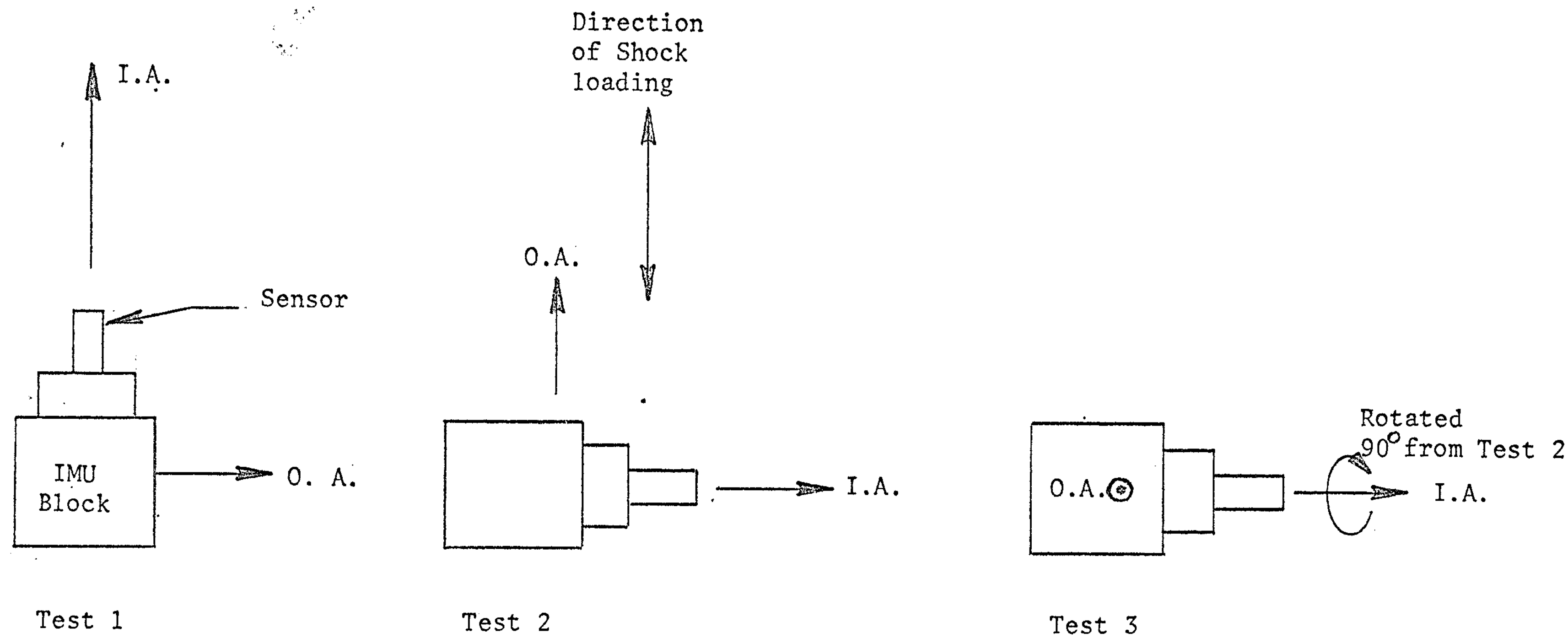


Figure B-12. Orientation of Unit during Shock Test

	Fixed Clamp Alignment					Adjustable Clamp Alignment					
	Input Axis				Output Axis	Input Axis				Output Axis	
	O.A. Upright		O.A. Inverted			O.A. Upright		O.A. Inverted			
	x Component	y Component	x Component	y Component		x Component	y Component	x Component	y Component		
1											Initial Reading
2											After Shock, (Test 1, Fig B12)
1											Initial Reading
2											After Shock, (Test 2, Fig B 12)
1											Initial Reading
2											After Shock (Test 3, Fig B 12)

(All readings in arc secs)

Table B-11. Shock Test

Appendix C

NEW TECHNOLOGY CLAUSE

After a diligent review of the work performed under this contract, no new innovation, discovery, improvement or invention was made.