TA165
.M41
.I591
no. E-2246

Aero

MASS. INST. TECH.
AUG 12 1969
LIBRARIES

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

APOLLO

GUIDANCE AND NAVIGATION

E-2246

COMPUTER-AIDED INERTIAL PLATFORM REALIGNMENT IN MANNED SPACE FLIGHT

by
James A. Hand

MAY 1968

MIT INSTRUMENTATION LABORATORY

CAMBRIDGE 39, MASSACHUSETTS

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

APOLLO

GUIDANCE AND NAVIGATION

Approved: Ain Laats Date: 23 May 1968
A. LAATS, DIRECTOR, SYSTEM TEST GROUP
APOLLO GUIDANCE AND NAVIGATION PROGRAM

Approved: David G. Hoag Date: 22 May 68
DAVID G. HOAG, DIRECTOR
APOLLO GUIDANCE AND NAVIGATION PROGRAM

Approved: Ralph R. Ragan Date: 23 May 68
RALPH R. RAGAN, DEPUTY DIRECTOR
INSTRUMENTATION LABORATORY

E-2246

COMPUTER-AIDED INERTIAL PLATFORM REALIGNMENT IN MANNED SPACE FLIGHT

by
James A. Hand

MAY 1968

MIT INSTRUMENTATION LABORATORY
CAMBRIDGE 39, MASSACHUSETTS

To be presented at AIAA 2nd Guidance,
Control and Flight Dynamics Conference
August 12-14, 1968, Pasadena, California.

ACKNOWLEDGEMENT

This report was prepared under DSR Project 55-38200, sponsored by the Manned Spacecraft Center of the National Aeronautics and Space Administration through Contract NAS 9-4065 with the Instrumentation Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts.

Many engineers at MIT share the author's concept of the usefulness of the fully automatic IMU realignment capability. Special thanks are given to A. Laats, R. Crisp and R. Lones for encouraging the development work; to E. Grace for his superb computer programming efforts, and to V. Megna, for sharing the long nights of system testing.

The publication of this report does not constitute approval by the National Aeronautics and Space Administration of the findings or the conclusions contained therein. It is published only for the exchange and stimulation of ideas.

RECEIVED
AUG 12 1969
M. I. T. LIBRARIES

COMPUTER-AIDED INERTIAL PLATFORM REALIGNMENT IN MANNED SPACE FLIGHT

James A. Hand

Instrumentation Laboratory
Massachusetts Institute of Technology
Cambridge, Massachusetts

Abstract

Manually conducted star sightings necessary to realign an inertial platform during long-term manned space flights are, at best, a time consuming task. At worst, these sightings can be critically time consuming since they are prerequisite to accurate spacecraft guidance and control functions; e.g. reentry maneuvers.

Through establishment of logical communications between a star tracker, a computer and a previously aligned inertial platform, it has been shown practical to bypass the manual sighting function and execute optics pointing, search moding, target acquisition and data processing such that a completely automatic realignment is accomplished. The technology represented by the Apollo Guidance and Navigation System is the foundation for developing this automatic inertial platform realignment capability. The new capability is being considered for an Apollo Applications Program experiment to be conducted from low earth orbit.

1. Introduction

Having first determined the orientation of the Inertial Measurement Unit (IMU) through sightings on two preselected navigational stars, it will be possible for the Apollo astronauts to rely on the accuracy of this alignment for a matter of several hours[1]. However, accumulation of random uncertainty errors in gyroscope drift terms will render it advisable to conduct periodically (e.g., every three hours) two additional sightings for inertial realignment purposes. Also, two such sightings will be necessary at any time it becomes desirable to perform IMU mode changes from one inertial attitude, through a spacecraft-fixed orientation ("coarse alignment"), to another inertial attitude.

One may readily see that the above sets of added star sightings and associated computer operations can become a tiresome chore on long-term manned flights (e.g., Apollo Applications Missions). By way of example, the performance of a manually accomplished realignment program takes in the range of 13 to 38 computer operations;[2] coordinated operation of the optics in a zero-g environment and execution of an accurate sighting "mark" on each of the two selected/recognized/acquired navigation stars. The ten to fifteen minutes required to manually perform the realignment procedure might also represent time well used for other tasks in a situation where it became necessary to prepare for a time-critical guidance and control maneuver; for instance re-entry.

An experiment concerning inflight star-horizon sightings for on-board navigation is being prepared by the MIT Instrumentation Laboratory for the Apollo Applications Program[3]. Since the experiment involves use of a star tracker in conjunction with the Optical Subsystem, it is a rather interesting system engineering task to provide the capability for automatically realigning the IMU upon astronaut request. In fact, a recent series of G & N System tests at the Instrumentation Laboratory have proven this added capability a practical matter[4].

The plan of this paper is first to briefly review the hardware design and functions of the basic Apollo G & N System where pertinent to the IMU realignment problem. The existing set of computer programs and routines related to the same problem are then outlined, thereby formulating the baseline for a description of star tracker/computer communications which are being established for the automatic realignment capability. A discussion on star tracker design is also included. Finally, the system tests, which included a comprehensive simulation of the inflight realignment task, and results are described.

533774

2. Apollo Guidance and Navigation System Description

The Command Module Guidance and Navigation System, designed for completely self-contained guidance, navigation and control functions in earth orbital or lunar missions, is comprised of three major subsystems; the Optical, the Computer and the Inertial (Figure 1). Other important elements of the System are the Power Servo Assembly (PSA), the Coupling Data Units (CDU), the Display and Keyboard Assembly (DSKY), (Fig. 2), and the Display and Control panels (D&C).

The optics include a single-line-of-sight, sixty-degree field-of-view Scanning Telescope (SCT) which is used as a finder and back-up device for the 1.8-degree field, dual-line-of-sight Sextant (SXT) (Fig. 3). Both instruments have two degrees of freedom (Shaft and Trunnion) and are contained in one unit which is mounted and co-aligned on a common navigation base with the IMU (Figure 4). Control of the optics for mode switching and line-of-sight commands are provided respectively through a set of switches mounted directly below the optical unit and by a rotational hand controller providing proportional control in three speed regions to limits of 18 deg./sec. shaft angle and 8 deg./sec. trunnion angle. Either direct shaft and trunnion or resolved modes of line-of-sight motion can be commanded through the hand controller. A computer controlled mode of operation is provided for line-of-sight drive at fixed rates of approximately 15 deg./sec. shaft angle and 4 deg./sec. trunnion angle. The position readout of shaft and trunnion is provided through 16 speed and 64 speed resolvers respectively which are first converted to digital quantities in the electronic CDU. On execution of a sighting "mark", these angle readouts are interrogated in the computer and stored for processing.

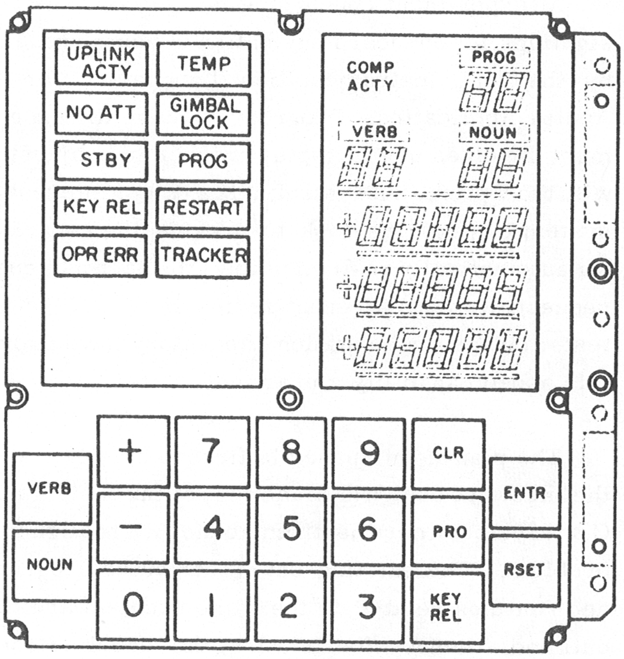

Fig. 2 Block II Display and Keyboard Assembly (DSKY).

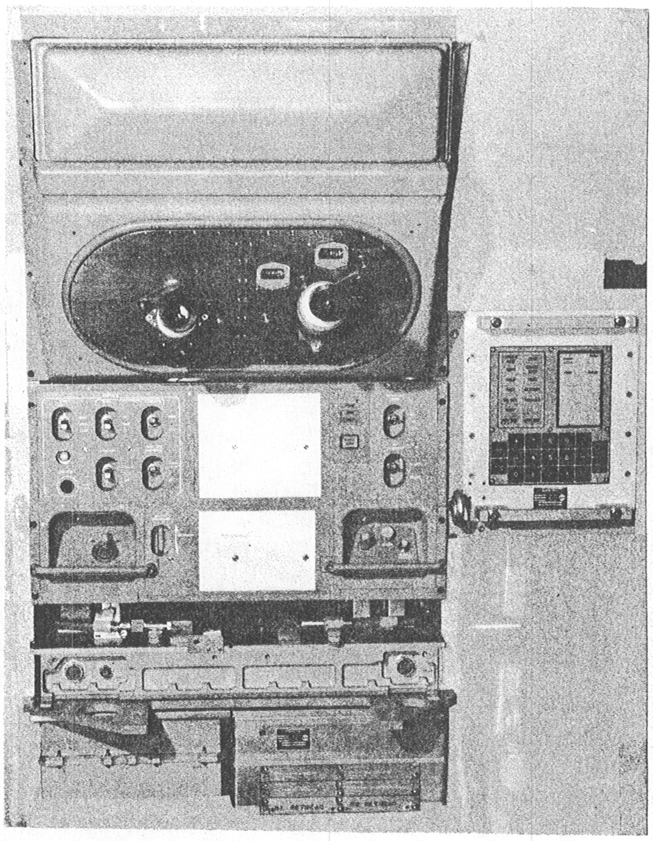

Fig. 1 G&N System - Command Module Lower Equipment Bay.

The computer contains 38,912 locations in memory, divided into 2048 erasable and 36,864 fixed storage addresses. Sixteen bits comprise one fixed decimal point data word; one bit for parity, one for sign and the remainder for data. Data can be manipulated in single, double and triple precision quantities through the one's complement arithmetic form. Mean Cycle Time for each arithmetic operation is 12 microseconds.

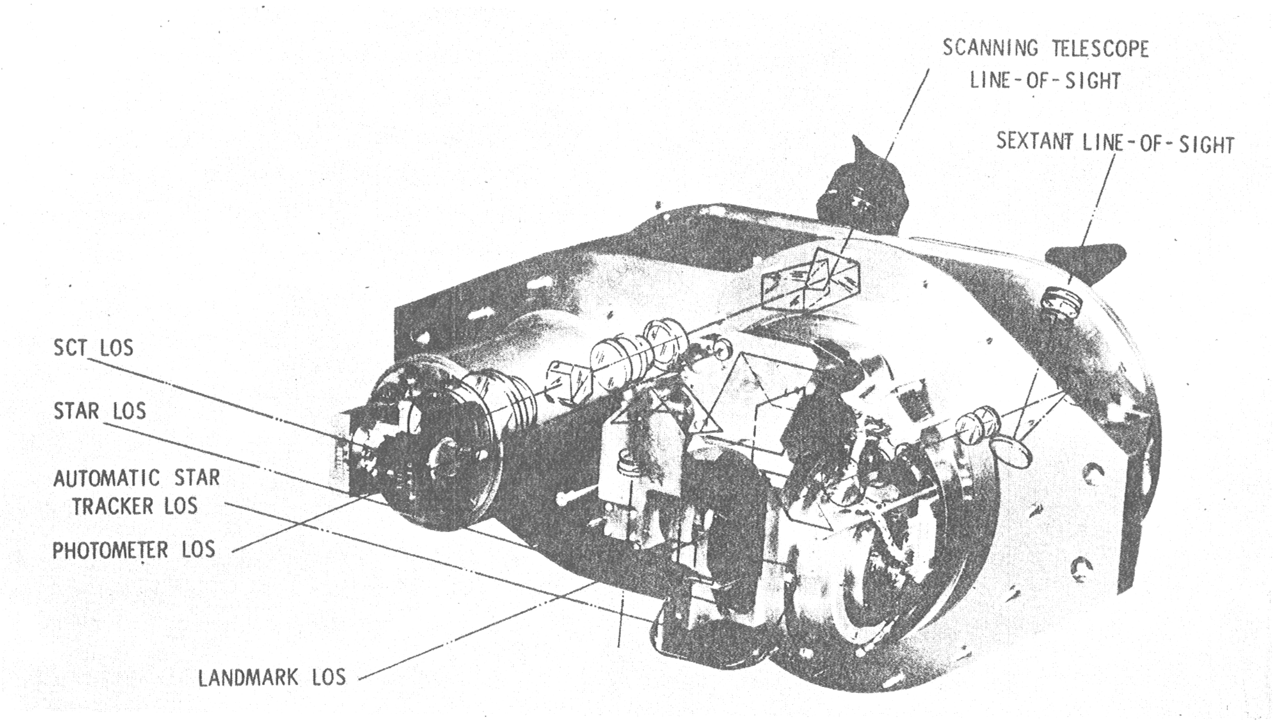

Fig. 3 Apollo Optical Unit.

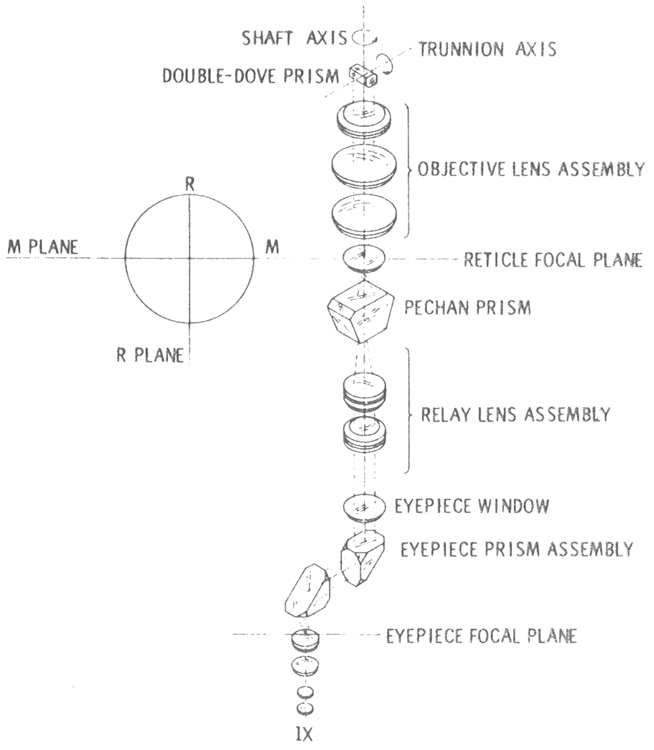

Fig. 3a SCT Optics.

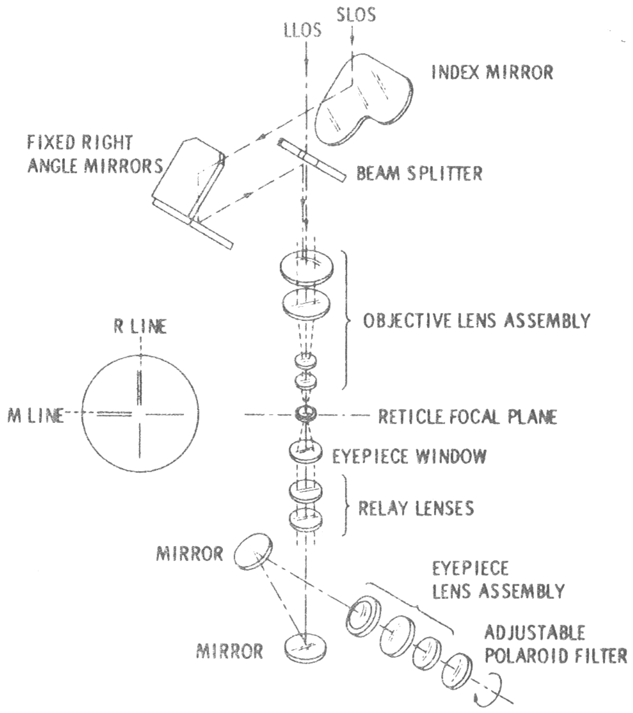

Fig. 3b SXT Optics.

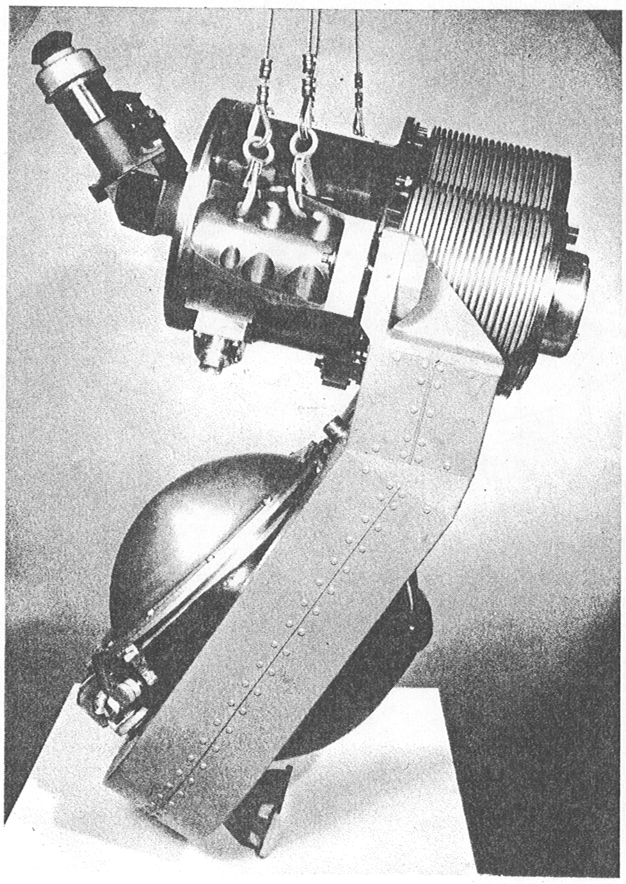

Fig. 4 Optics and IMU on NAVBASE.

For our purposes the most important aspect of the computer is the DSKY. This instrument interfaces directly with the astronaut; displays the major modes of computer operation; the verb-noun codes (operator-operand) and the data contained in storage (see Figure 2). It also displays and accepts commands or data loads from the astronaut in unsigned octal or signed decimal form. The data displays are comprised of a sign location and five numerical locations in each of three registers. Special lights and codes are provided for indicating operational options permitted, Astronaut response requests and alarm conditions. Momentarily, we shall return to the operation of the display and command keyboard in more detail.

The IMU has three degrees-of-freedom which permit 360 degrees rotation about the outer and inner gimbal axes and nominally 60 degrees about the middle gimbal (85 deg. max.). In the 0, 0, 0 angle positional configuration, rotation about the body-fixed outer gimbal corresponds to roll, the inner gimbal to pitch and the middle gimbal to yaw. Mounted orthogonally on the stable member are three Inertial Reference Integrating Gyros (IRIGs) and three Pulsed Integrating Pendulums (PIPs). The operational modes include capabilities for alignment to the spacecraft fixed frame through the servo loop and to any pre-selected inertial frame by pulse-torquing the gyros. Angular sensing of spacecraft attitude with respect to the stable member is via a 16-speed and a 1-speed resolver loop. Spacecraft attitude stabilization is performed through computation of a set of desired gimbal angles, generation of an error signal between actual and desired attitude and then commands to the spacecraft reaction control system to null out this error.

Having briefly refreshed our memory on the general characteristics of the G & N System,[5, 6, 7] let us exercise imagination and don the Astronaut Navigator spacesuit, launch into a 150-nautical-mile earth orbit and conduct an inflight IMU realignment. The ground rules governing this exercise are:

a) the spacecraft is in a configuration known by the computer (example: Service Module attached to Command Module) for purposes of utilizing the correct autopilot parameters,

b) stabilization of the craft can be manual, controlled by the G & N system or controlled by the Stabilization and Control System depending upon choice, and

c) the computer "knows" roughly the inertial orientation of the stable member (e.g., ±0.1 deg) and this error is due solely to gyro drift since the original orientation determination was completed. This assumption means simply that gimbal lock or power interruption has not occurred since IMU orientation was established by sighting on two stars and computing stable member attitude via a reference rotation matrix to the star vectors which are stored in a basic coordinate frame. The last ground rule is that the entire realignment problem is a one-man exercise.

There are three distinct orientations to which the stable member may be realigned, namely: "REFSMMAT", a "preferred" and a "nominal" orientation. Realignment to REFSMMAT refers to the rotation transformation matrix which describes stable member orientation in the basic geocentric reference coordinate system. Thus, in this case, gyroscope drift is negated by torquing the stable member back to its originally established orientation. The preferred orientation is one which had been previously defined through operation of another program. The nominal inertial attitude is defined by aligning at a selected time the $+Z_{SM}$ axis along the position vector toward earth, the Y_{SM} axis orthogonal to velocity and position vectors and the X_{SM} axis to complete the right-handed triad. For this case, realignment to the REFSMMAT orientation will be selected to simplify matters and so that zero gyro torquing angles are predictable for the case where negligible gyro drift had occurred.

To indicate selection of the realignment program (P 52) to the computer, its corresponding code is keyed in: Verb 37, Enter ("change major mode"), 52 Enter. Correspondingly, the major mode light is changed, an automatic routine checks that the IMU is turned on, that the original REFSMMAT is valid, etc. A flashing display requests that the operator select one of the three orientations available. Verb 22 Enter, 00003 Enter is keyed in to indicate the REFSMMAT selection, or a PROCEED button is depressed if this orientation had been suggested by the computer.

A flashing display code now requests that two suitable navigation stars (of the 37 stored in memory) be acquired within the cone of view of the optics; i.e., within about 45 degrees of the optics shaft axis. Concurrently, a code is keyed in to permit monitoring of IMU gimbal angles (Verb 16, Noun 20, Enter). Hence the problem is to look for targets in the Scanning Telescope field-of-view, while maneuvering the craft at the same time. The instantaneous field of the telescope is a 30-degree half-angle cone and the cone-of-view (the available unvignetted area) is a 45-degree half-angle so manual drive of the optics is also required to scan this area (Figure 5). Once the operator indicates that the targets are in view, the computer will flash a star code which identifies one of the two stars by number, or it will flash an alarm if subsequent spacecraft rotations have caused either of the targets to leave the cone-of-view. Assuming this has not happened, the operator may agree with the star code displayed and permit the computer to automatically drive the optics such that the first target is placed within the 1.8-degree Sextant field.

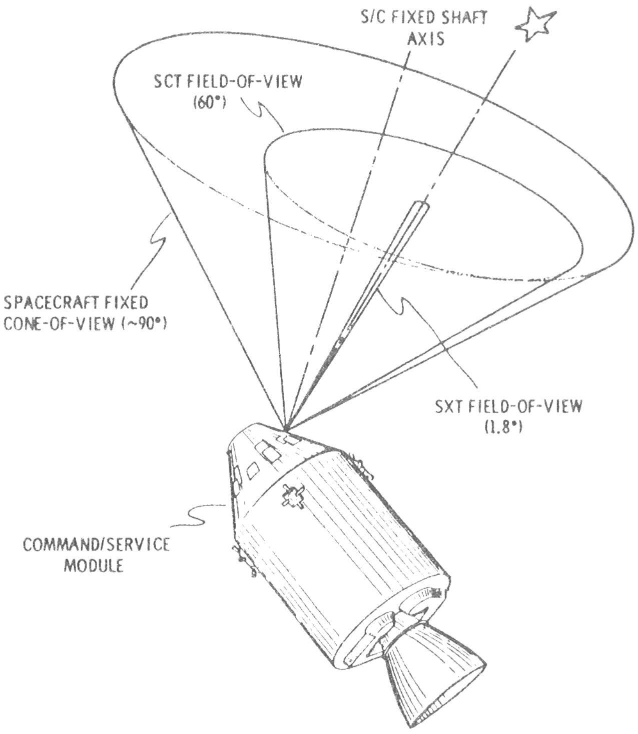

Fig. 5 Optical Subsystem Cones and Fields-of-View.

As noted previously, the computer has knowledge of the approximate inertial orientation of the IMU. The present exercise is to improve that knowledge by new sighting marks. Also, available in storage are the transformations necessary to convert from stable member coordinates to navigation base coordinates to optics coordinates (Figure 6). An automatic optics routine can use this knowledge to compute a line-of-sight to the selected star and then drive the optics accordingly. The error in pointing the optics will be a function of error in stable member orientation and some second-order errors due to optics misalignments. However, as one might suspect, the automatic optics capability will be a major building block for the automated realignment function being designed. This will be discussed shortly.

Getting back to the realignment problem in progress, we have permitted the computer to drive the optics to the first target. Now, by taking manual

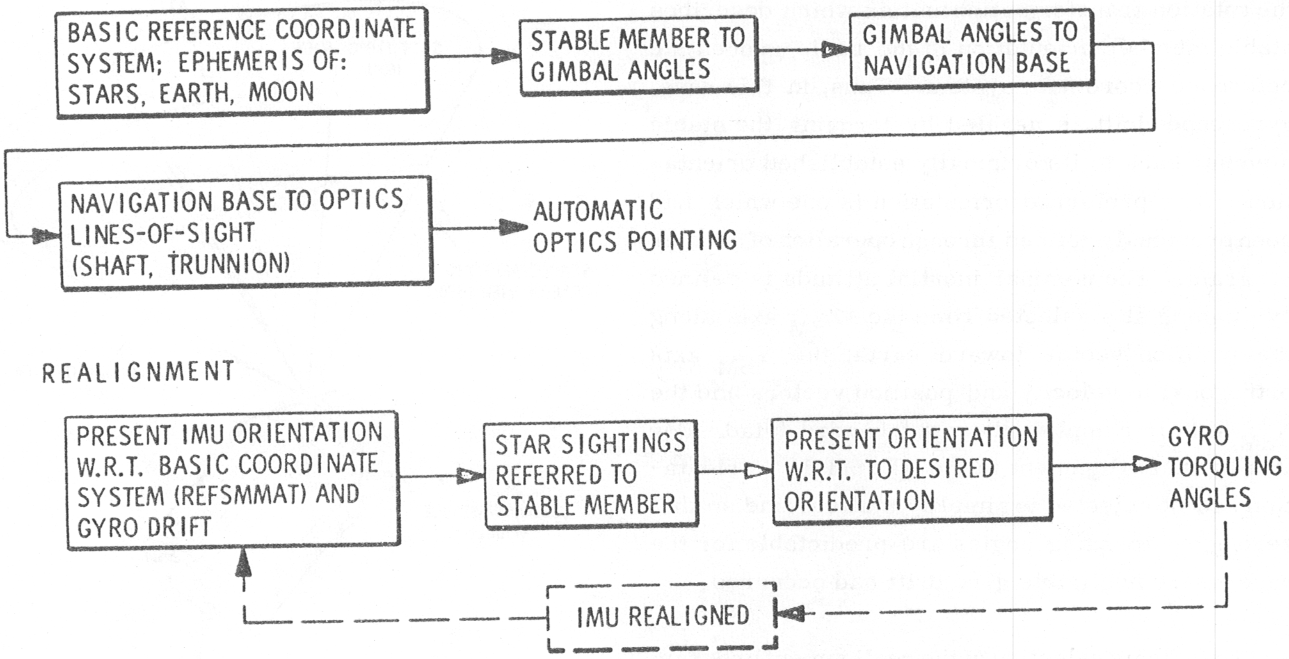

Fig. 6 Block Diagram, Computer Contained Transformations.

control (mode switch) the target is aligned in the Sextant reticle and a mark button is depressed. At this instant the computer reads the optics and IMU gimbal angles and the time and stores this data. After repeating the star selection, optics driving, and sighting procedure on the second target, the computer can determine present stable member orientation and develop a rotation matrix for pulse torquing the stable member back to the REFSMMAT (desired) orientation. Flashing displays show the Astronaut the error made in sighting on the two stars (stored vs. measured angular separation), final gimbal angles and delta torquing angles computed. If he indicates agreement on all displayed data and rejects the option to sight on a third star for checking purposes, gyro torquing is automatically performed and realignment is achieved.

The problem just completed might be called the "minimum" realignment program, i.e., thirteen operations were required and 32 keyboard depressions were needed (Fig. 7). Many other alternatives are available in the "maximum" program (Figure 8) such that up to 38 operations - 135 key depressions - could be required. (Incidently, one of the important alternatives involves permitting the computer to command attitude maneuvers such that a preferred line-of-sight establishes the target in the field of

No.	Operation Description	Number of Switch/Key Depressions
1	Call Program 52 (IMU Realignment Program)	7 keys
2	Load "REFSMMAT" realignment option	6
3	Maneuver Spacecraft (Manual)	1 plus rotation control
4	Accept star code selected by computer	1
5	Switch optics mode to computer control	1 switch
6	Switch optics mode to MANUAL	1 switch
7	Perform sighting mark	1 button
8	Terminate marking	1
9	Repeat sighting on second star	3
10	Confirm star sighted codes	1
11	Torque gyro's	1
12	Reject Fine Align check	1
13	Call Program 00 (Idling Program)	7

TOTALS: 13 operations
32 key and switch
depressions

Fig. 7 Operations and Key Depressions, "Minimum" Realignment Program.

view of the Scanning Telescope and Sextant.) Any well trained and coordinated system operator could complete the "minimum" exercise in about ten minutes, excluding time required for attitude maneuvers. According to the author's experience, the "maximum" program takes about fifteen minutes in the laboratory environment. Until flight experience is accumulated on manned Apollo Missions, it is uncertain whether the free-fall environment, which makes coordinated body movements difficult, will significantly lengthen the time required for completing realignment.

No.	Operation Description	Number of Switch/Key Depressions
1	Call Programs 52 (IMU Realignment Program)	7 keys
2	Load "Nominal" Realignment option	6
3	Load Ground Elapsed Time for realignment	22
4	Maneuver spacecraft	Rotation Hand Controller
5	Call gimbal angles desired display	4
6	Monitor Coarse Align-Inertial Mode Change	1
7	Maneuver vehicle (Monitor gimbal angles)	9
8	Reload selected star code	7
9	Switch optics to computer control	1 switch
10	Optics mode to MANUAL	1 switch
11	Perform sighting mark	1 button
12	Terminate marking	1
13	Reload selected star	7
14	Optics mode to computer control	1
15	Reload star code	7
16	Optics mode to MANUAL	1
17	Mark	1 button
18	Terminate Marking	1
19	Reload star code	7
20	Accept sighting error displayed	1
21	Torque gyros	1
22	Accept third star sighting check (Recycle to Step 8)	1
23	Reject sighting check on fourth star	1
24	Call Program 00 (Idling Program)	7

TOTALS: 38 operations with recycle
135 key and switch depressions

Fig. 8 Operations and Key Depressions, "Maximum" Realignment Program.

Some interesting characteristics of the above realignment exercise are:

a) Virtually all of the "building block" computer routines are already available for automating the process.

b) From astronaut and computer knowledge about present orientation (spacecraft and stable member) it is possible to generally predict results and thus rearrange decisions such that they are made in the beginning and the very end of the process rather than throughout it. That is, one may establish the assumption that the astronaut will agree with all automatic options permitted, stars selected, etc. and will only interrupt the program if displays indicate optics or computer difficulties.

c) The only hardware element missing from the system is a star tracker capable of making the transition from the coarse automatic pointing mode to the accurate tracking/sighting mark mode.

3. Automatic IMU Realignment

The capability of the on-board computer to aid in IMU alignment through use of a star tracker may be briefly outlined.

First, the computer can rapidly calculate, then command the optics to a selected star line-of-sight and inertially maintain pointing if the IMU is on and aligned. Hence, the special advantage of being able to perform automatic search routines about the inertial line-of-sight may be realized.

Second, it is possible to employ the computer for checking the calculated line-of-sight against the line-of-sight achieved by the tracker when it is locked on the target. This function could be very useful in a situation where the scattered light environment (i.e., solar impingement, earth or lunar albedo) make target identification impractical through the 60-degree field Scanning Telescope. Of course, the self-check function could also reduce the probability of erroneous target identification by comparing accurately (±0.2 deg) the precalculated and final tracker line-of-sight with respect to the basic reference coordinate system (computer-stored star catalogue).

Thirdly, the rapidity with which the computer can repetitively interrogate and process the star tracker gimbal angle data is measured in tens of milliseconds — much faster than is humanly possible to sight and mark on a target. Thus, the rapid data processing capability provides for minimizing pointing errors by averaging both optics and IMU gimbal data when tracking a star.

Lastly, the very precise inertial vectors thus established, (through two or three star sighting sequences) would make apparent any out-of-tolerance gyro drift conditions.

The star tracker now in final development for the reference AAP experiment[8] will be an integral component of the Sextant optics and aligned with the movable star line-of-sight (trunnion). The instantaneous tracker field is shown superimposed with that of the Sextant in Fig. 9.

Figure 10 illustrates the star tracker in block diagram form. The instrument has a square field of view (0.6 degree, diagonal) and is designed for accurately tracking stars from -1.6 to +3.0 magnitude, S-4 response. Functionally, the tracker tuning forks modulate the star light along two axes; then current pulses from the photomultiplier tube are amplified and frequency discriminated in a manner whereby the fundamental and harmonic, when detected and summed, provide automatic gain control for the power supply. This summation also lights an acquisition indicator on the control panel and sends the "star acquired" signal to the computer. Concurrently, the fundamental frequency for each axis, after demodulation, is used as an error signal to drive the shaft and trunnion motors. That is, the tracker functions as a nulling device — since the fundamental component of modulated starlight is linearly proportional to the angular distance from the optical axis of the instrument, this signal is used to maintain the target line-of-sight. The error null for this device is ±45 arc seconds, three sigma, when tracking at +3.0 magnitude star[9].

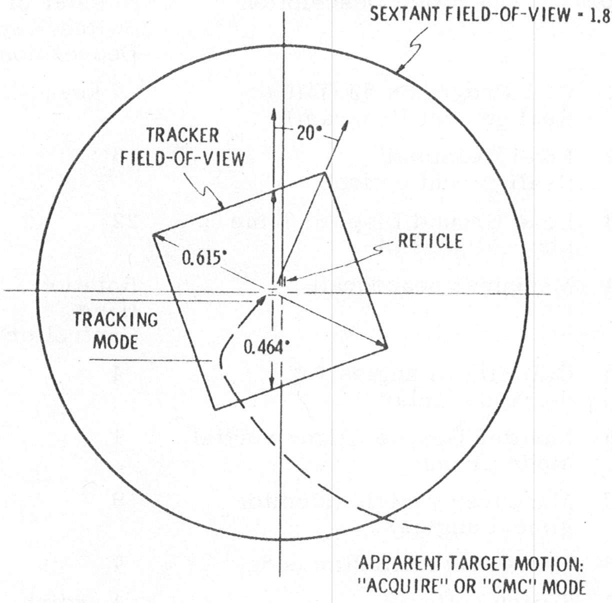

Fig. 9 Star Tracker and Sextant Fields of View.

The tracker automatic gain control is set at a nominal value of 200 volts/radian. This results in the expiration of less than one second to null the error signal when the loop is closed on a target initially offset about 10 arc minutes in the field-of-view. Overshoot from the null position for tests on a breadboard star tracker was approximately one arc minute.

The communications between star tracker and computer include a signal to turn the tracker on, as commanded by a mode switch, and a signal which disengages the automatic optics-drive signal (Fig. 11). This disengagement permits the tracker to close the loop to the Sextant motor drives when target acquisition by the tracker is sensed.

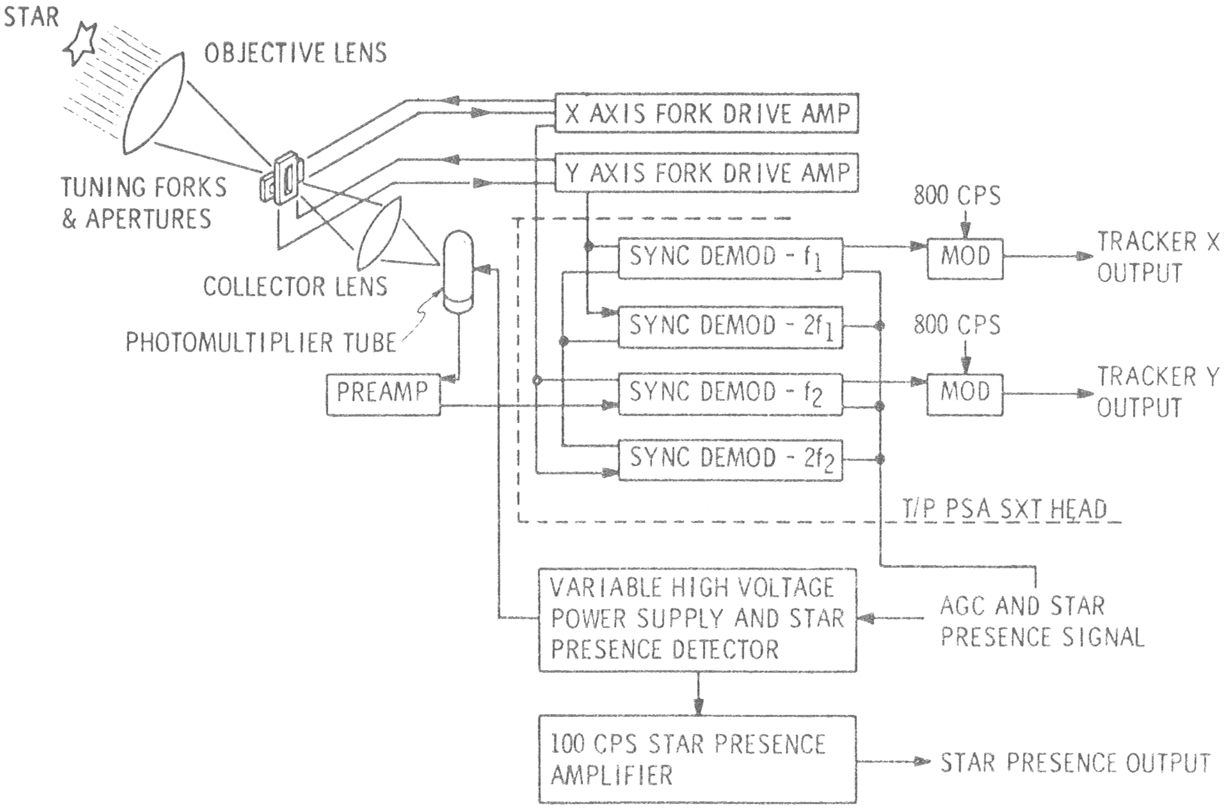

Fig. 10 Star Tracker, Block Diagram.

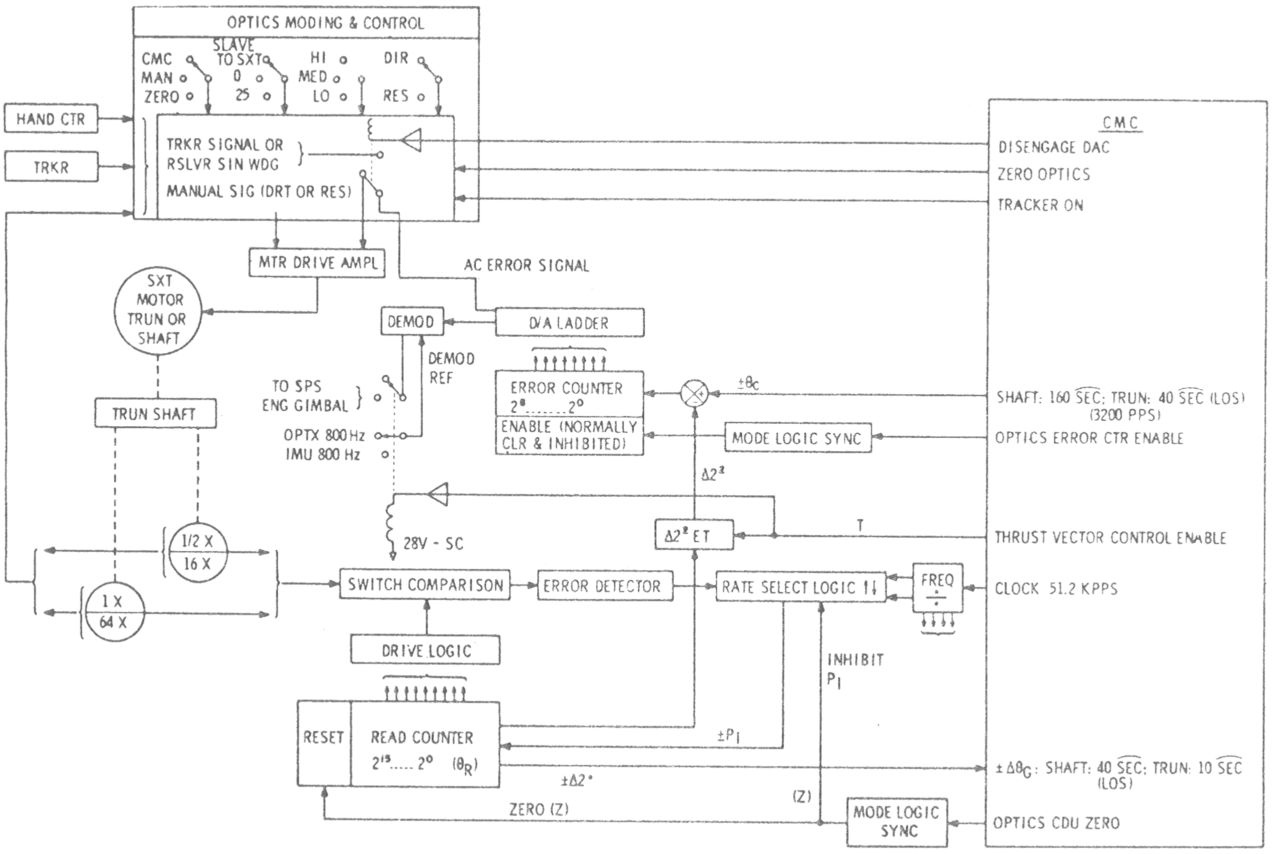

Fig. 11 Optics - CDU Moding - Block II CSM.

As one may imagine, the fundamental design objective is to arrange the tracker/computer/tracker logic such that the optics are driven to the correct line-of-sight and the tracking loop is permitted to close at the instant the acquisition signal is received. Once tracking is accomplished, the computer may interrogate optics and IMU gimbal angles at a high rate (e.g., 3 marks at one per 50 ms), and process the averaged data as if these were sighting marks made by a superfast Astronaut. Having sampled the data for the first star, automatic optics may be re-engaged to drive the second star and then the process is repeated.

Three related problems must be overcome to achieve the above objective: the rate at which the target initially moves through the field is extremely high (average 15 deg/sec shaft, 4 deg/sec trunnion); pointing errors will exist such that the star will not generally pass through the center of the field nor end there, and interrogation of the acquisition signal is digital. The rate problem is due to overshoot of the automatic optics positioning loop. Measurements indicate about six degrees overshoot in shaft angle and one degree in trunnion. Hence, if a pointing error exists such that it cannot be assumed the target will be in the field at the completion of the automatic optics routine, then acquisition must be attempted on the first pass. Also, a search routine is required, should acquisition and tracker loop closure not occur after the automatic optics loop is initially disengaged. Finally, the acquisition is sent to the computer via a relay taking about 30 milliseconds to close. The computer interrogates this relay periodically, with the fastest rate set at 10 milliseconds per interrogation. A relay is then opened to disengage the optics drive, consuming another 10 milliseconds, and resulting in a total of 50 milliseconds to successfully close the tracking loop.

The tracker pointing strategy must consider all factors which will optimize the probability of successful acquisition through maximizing the time when the target is in the field-of-view. For example, the present star selection routine contains the criteria that the two targets have angular separation of 40 degrees and lie within 45 degrees of the optics shaft axis. Obviously, since the targets are point sources at infinity, the high rate of automatic shaft angle drive rate would be unimportant if the shaft axis is initially pointed very near the target chosen. Therefore, by modifying the star selection routine to add the criterion that the target lies near this pole will render the high shaft drive rate relatively unimportant. As previously noted, an automatic preferred spacecraft attitude routine is available in the computer. This routine can be used to point the shaft axis along desired lines-of-sight once each target is selected.

In February 1968, a star tracker test program was undertaken at the Instrumentation Laboratory on a Space Navigator Simulator which permits exercising the entire Apollo Guidance and Navigation System (Fig. 12). The objectives of this program included demonstrating star tracker measurement accuracy under dynamic base-motion conditions and demonstration of optics mode transitions from the automatic pointing routine to tracking.

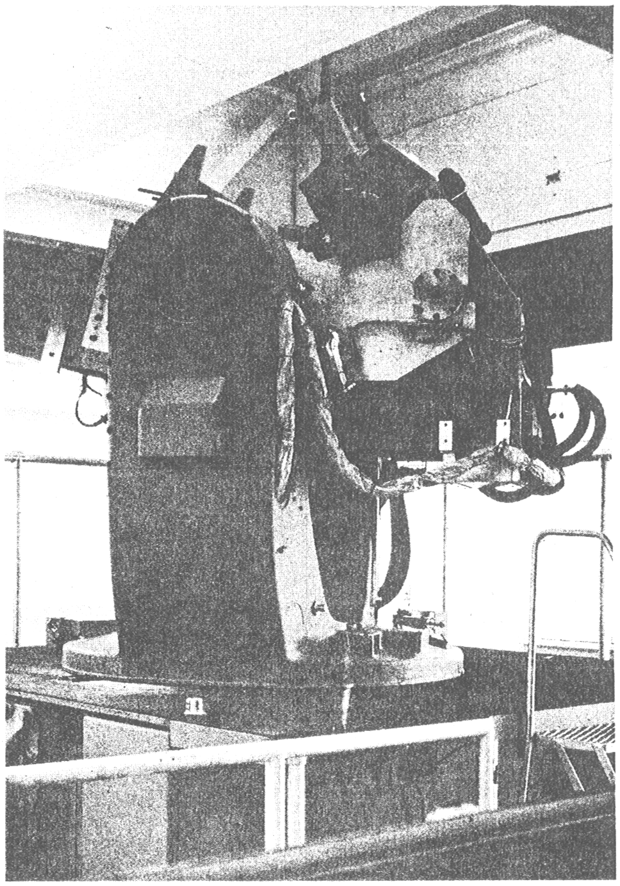

Fig. 12 Apollo Space Navigator Simulator.

A special computer routine was added to the existing realignment program for the purpose of automatically disengaging optics driving upon receipt of the acquisition signal from the tracker (Fig. 13). This preliminary erasable routine was also designed to perform tracker turn-on through interrogation of a mode switch on the System control panel and to re-engage automatic optics driving after indication that a mark had been executed on each selected target. Thus, the capability for demonstrating the feasibility of automatic IMU realignment was provided with the exceptions of a tracker search routine and automatic sighting marks.

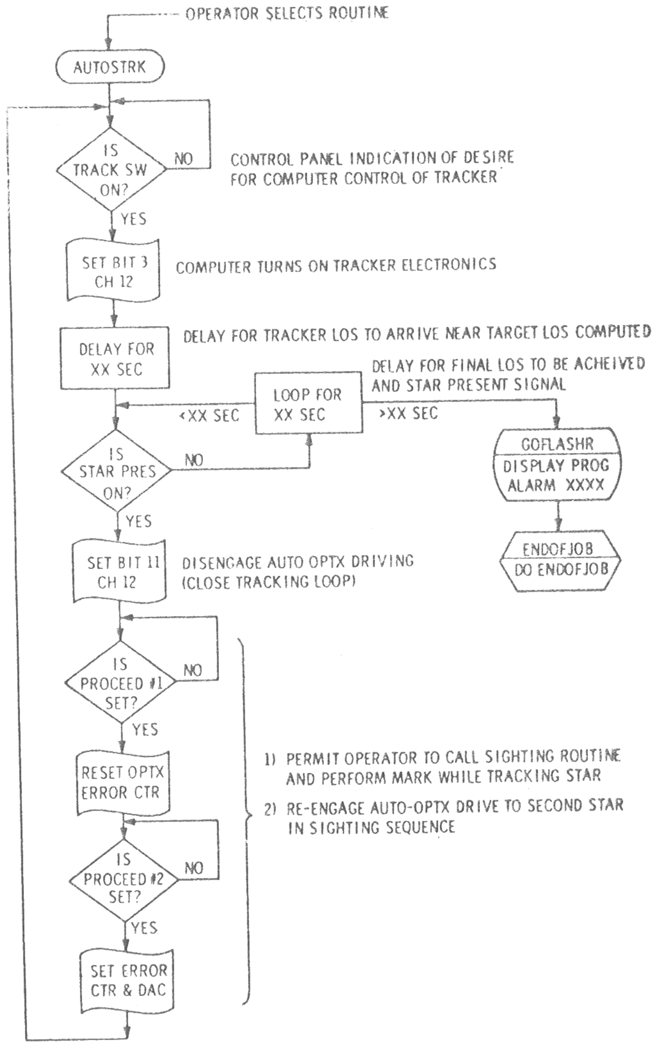

Fig. 13 Logic Diagram, Routine AUTOSTRK.

A.

STARS TRACKED	MAGNITUDE (VISUAL)	(S-4)
Sirius	-1.6	-1.6
Rigel	+0.3	+0.2
Alkaid	+1.9	+1.6
Polaris	+2.1	approx 3.4
Dnoces	+3.1	+3.4

B. VISUALLY ESTIMATED STATIC ERROR (i.e. jitter)

Sirius	< 1.0 arc min
Rigel	< 1.0 arc min
Alkaid	approx. 1.0 arc min
Polaris	approx. 1.0 arc min
Dnoces	approx. 1.0 arc min

C. BASE MOTION TEST - 1°/SECOND; ONE AXIS; LESS THAN 2.5 ARC MINUTES TOTAL STATIC ERROR

D. SCATTERED LIGHT TEST - TRACKED RIGEL AT 37.5 DEGREES TO 3/4 MOON

Fig. 14 Summary of Star Tracker Test Results.

The stated test objectives were achieved (Fig. 14). The tracker reached an acceptable static error (1.0 arc minute/axis) after approximately two seconds when being subjected to the highest expected step motion inputs of one degree/second. Automatically the System selected targets of opportunity and pointed the optics, whereupon the transition to tracking was made. After performance of a manual sighting mark in the tracking mode, the optics drive was re-engaged; then slewing to the next target occurred and the tracking transition was repeated. The total sighting error never exceeded 2.5 arc minutes for stars including the range from Dnoces to Sirius (+ 3.1 to - 1.6 visual magnitude).

4. Conclusion

Development of an automatic IMU realignment capability seems a worthwhile objective for long-term manned space missions. Cursory investigation and test indicates that the realignment process can be reduced from consuming 10 to 15 minutes per exercise to perhaps one minute, excluding in both cases prerequisite spacecraft attitude maneuvers.

At this writing, work is continuing on development of computer-controlled search routines, automatic mark routines and the many other test programs that must be completed before the stated objective can be realized in manned flight.

Acknowledgement

This report was prepared under DSR Project 55-38200, sponsored by the Manned Spacecraft Center of the National Aeronautics and Space Administration through Contract NAS 9-4065 with the Instrumentation Laboratory, Massachusetts Institute of Technology, Cambridge, Mass.

Many engineers at MIT share the author's concept of the usefulness of the fully automatic IMU realignment capability. Special thanks are given to A. Laats, R. Crisp and R. Lones for encouraging the development work; to E. Grace for his superb computer programming efforts, and to V. Megna, for sharing the long nights of system testing.

The publication of this report does not constitute approval by the National Aeronautics and Space Administration of the findings or the conclusions contained therein. It is published only for the exchange and stimulation of ideas.

References and Notes

1. MIT/IL Document No. R-547, Rev. 1, Guidance System Operation Plan for Manned CM Earth Orbital Mission Using Program SUNDISK, (November 1967).

2. Ibid, Sect. 4, Program No. 52. (IMU Realignment Program).

3. Experiment No. M 439, Star-Horizon Measurements for On-Board Navigation, NASA, (November 2, 1966).

4. Hand, J.A., "Results of Star Tracker/Horizon Photometer Tests on the Space Navigator Simulator, MIT/IL System Test Group Memorandum No. 1119, (February, 1968).

5. Hoag, D.G., Apollo Guidance and Navigation - A Problem in Man-Machine Integration, MIT/IL, (1963).

6. Hand, J.A., A General Discourse on Celestial Navigation with the Apollo Optical Subsystems, Kollsman Instrument Corp., (January, 1965).

7. Green, A.I., and Filene, R.J., Keyboard and Display Program and Operation, MIT/IL Report No. E-2129, (June, 1967).

8. The AAP experiment optics also includes a fixed line-of-sight Horizon Photometer. Since the Horizon Photometer usage is not pertinent to IMU realignment; its description is left to a future paper.

9. Hand, J.A., "Results of System Tests on the Breadboard Star Tracker/Horizon Photometer (AAP Experiment No. M439)", MIT/IL System Test Group Memorandum No. 1097, (3 January 1968).

External:

NASA/RASPO	(1)
AC Electronics	(3)
Kollsman	(2)
Raytheon	(2)
Capt. M. Jensen (AFSC/MIT)	(1)

MSC: (21&1R)

National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas 77058
ATTN: Apollo Document Distribution Office (PA2) (18&1R)
C. Frasier (2)
T. Gibson (1)

KSC: (1R)

National Aeronautics and Space Administration
J.F. Kennedy Space Center
J.F. Kennedy Space Center, Florida 32899
ATTN: Technical Document Control Office

LRC: (2)

National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia
ATTN: Mr. A. T. Mattson

GAEC: (3&1R)

Grumman Aircraft Engineering Corporation
Data Operations and Services, Plant 25
Bethpage, Long Island, New York
ATTN: Mr. E. Stern

NAR: (18&1R)

North American Rockwell, Inc.
Space and Information Systems Division
12214 Lakewood Boulevard
Downey, California
ATTN: Apollo Data Requirements
Dept. 096-340, Bldg. 3, CA 99

NAR RASPO: (1)

NASA Resident Apollo Spacecraft Program Office
North American Rockwell, Inc.
Space and Information System Division
Downey, California 90241

AC RASPO: (1)

National Aeronautics and Space Administration
Resident Apollo Spacecraft Program Officer
Dept. 32-31
AC Electronics Division of General Motors
Milwaukee 1, Wisconsin
ATTN: Mr. W. Swingle

GE RASPO: (1)

NASA Daytona Beach Operations
P.O. Box 2500
Daytona Beach Florida 32015
ATTN: Mr. H. Lyman

R-577 Section 4
(Rev. 1)

DISTRIBUTION LIST

Internal

M. Adams (MIT/GAEC)
R. Ambrose
R. Battin
P. Bowditch
E. Copps
S. Copps
G. Cox
R. Crisp
J. Dahlen
G. Edmonds
J. Flanders
J. Fleming
J. Gilmore
K. Goodwin
E. Grace
J. Hand (15)
T. Hemker (MIT/NAR)
D. Hoag
I. Johnson
L.B. Johnson
M. Johnston
K. Kido
*J. Kingston
A. Kosmala
A. Laats
L. Larson
R. Larson
J. Lawrence
J. Lawson
D. Lickly (3)
F. Little
R. Lones
F. Martin
H. McOuat
V. Megna
J.E. Miller
H. Movitz
P. Nardella
J. Nevins
R. Ragan
P. Sarda
G. Schmidt
W. Schmidt (MIT/MSC)
G. Silver (MIT/MSC)
M. Trageser
K. Vincent
R. Weatherbee
R. Werner
R. Woodbury
L. Yorgy
Apollo Library (2)
MIT/IL Library (6)

*Letter of Transmittal only