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THE DESIGN AND DEVELOPMENT OF A SOLAR TRACKING UNIT

Irby W. Jones and James B. Miller*

ABSTRACT

The solar tracking unit was developed to support the Laser Heterodyne Spectrometer (LHS) airborne instrument, but has application to a general class of airborne solar occultation research instruments. The unit consists of a mirror mounted on two gimbals, one of which is hollow. The mirror reflects a 7.6 cm (3.0 in) diameter beam of sunlight through the hollow gimbal into the research instrument optical axis. A portion of the reflected sunlight is directed into a tracking telescope which uses a four-quadrant silicon detector to produce the servo error signals. The colinearity of the tracker output beam and the research instrument optical axis is maintained to better than ±1 arc-minute. The unit is microcomputer controlled and is capable of stand alone operation, including automatic Sun acquisition or operation under the control of the research instrument.

INTRODUCTION

The solar tracking unit was developed to support the Laser Heterodyne Spectrometer (LHS) instrument. This instrument is intended to fly on the NASA CV-990 aircraft to gather atmospheric spectroscopy data during a sunrise or a sunset. The instrument is shock mounted to the aircraft floor and must track the Sun through a window in the side of the aircraft. The alignment of the LHS instrument optical axis and the output beam from the tracking system is critical and requires the tracker to be mounted on the instrument. The solar tracker unit provides a stable 7.6 cm (3.0 in) diameter beam of sunlight to the instrument, compensating for both aircraft and instrument motion. The unit is microcomputer controlled and is capable of stand alone operation, including automatic Sun acquisition or operation under the control of the research instrument.

SPECIFICATION REQUIREMENTS

The following basic requirements are defined by the instrument science requirements or as a result of the overall instrument and aircraft interface design evolution.

- The unit must be mounted directly to the instrument optical table to eliminate relative motion between the tracker and the instrument.
- Weight must not exceed 18.1 kg (40 lbs).
- Mirror height above mounting surface must be 38.1 ±2.54 cm (15.0 ±1.0 in).

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* NASA Langley Research Center, Hampton, Virginia

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- A 7.62 cm (3.0 in) diameter sunbeam should be delivered to the instrument.
- Tracking stability and repeatability for each axis must be ±4 arc-minutes, with a goal of ±1 arc-minute.
- The tracking mirror reflecting surface must be optically flat to one-fifth wavelength at 0.63 microns.
- The optical line of sight (LOS) of the unit should be capable of being positioned to a local coordinate system with an accuracy and repeatability of ±1.0 arc-minute. Position control range should be +15° to -90° in elevation and ±180° in azimuth.
- The unit must be capable of tracking the Sun over an elevation range of +30° to -15° with no obscuration in the output beam.
- Frequency response must accommodate the expected range of aircraft disturbance. Frequency response goal for elevation axis is 100 Hz, and for azimuth axis is 25 Hz.
- A lockable stow position must be provided to protect the mirror optical surface and prevent motion in either axis.
- The system design should be as modular as possible to simplify testing and repair of the instrument in the field.
- The system must be simple to operate, test, and troubleshoot. It should be capable of monitering its own operation, diagnosing system faults, correcting the faults if possible, and notifying the system/operator in the event of a failure.

MECHANICAL DESIGN

The tracking unit design, which satisfies the requirements outlined above, is shown in Figure 1. A photograph of the completed unit and the control electronics is shown in Figure 2. The unit uses a mirror mounted on a horizontal elevation gimbal to reflect a sunbeam down through a hollow, vertical asimuth gimbal to a turning mirror, and onto the research instrument optical axis. A portion of the sunbeam is also reflected to a telescope which forms an image of the Sun on a photodiode detector. The detector produces error signals that cause the elevation and azimuth gimbals to move in a manner that keeps the Sun image on the detector.

The unit was built, assembled, and tested as three independent subsystems: an elevation gimbal, an azimuth gimbal, and a tracking sensor telescope. After subsystem testing, the three subsystems were integrated to form the complete solar tracking unit and system tests were performed. Figure 3(a) is a front view of the unit. Figure 3(b) shows the same view of the unit with the azimuth gimbal rotated approximately 180°.

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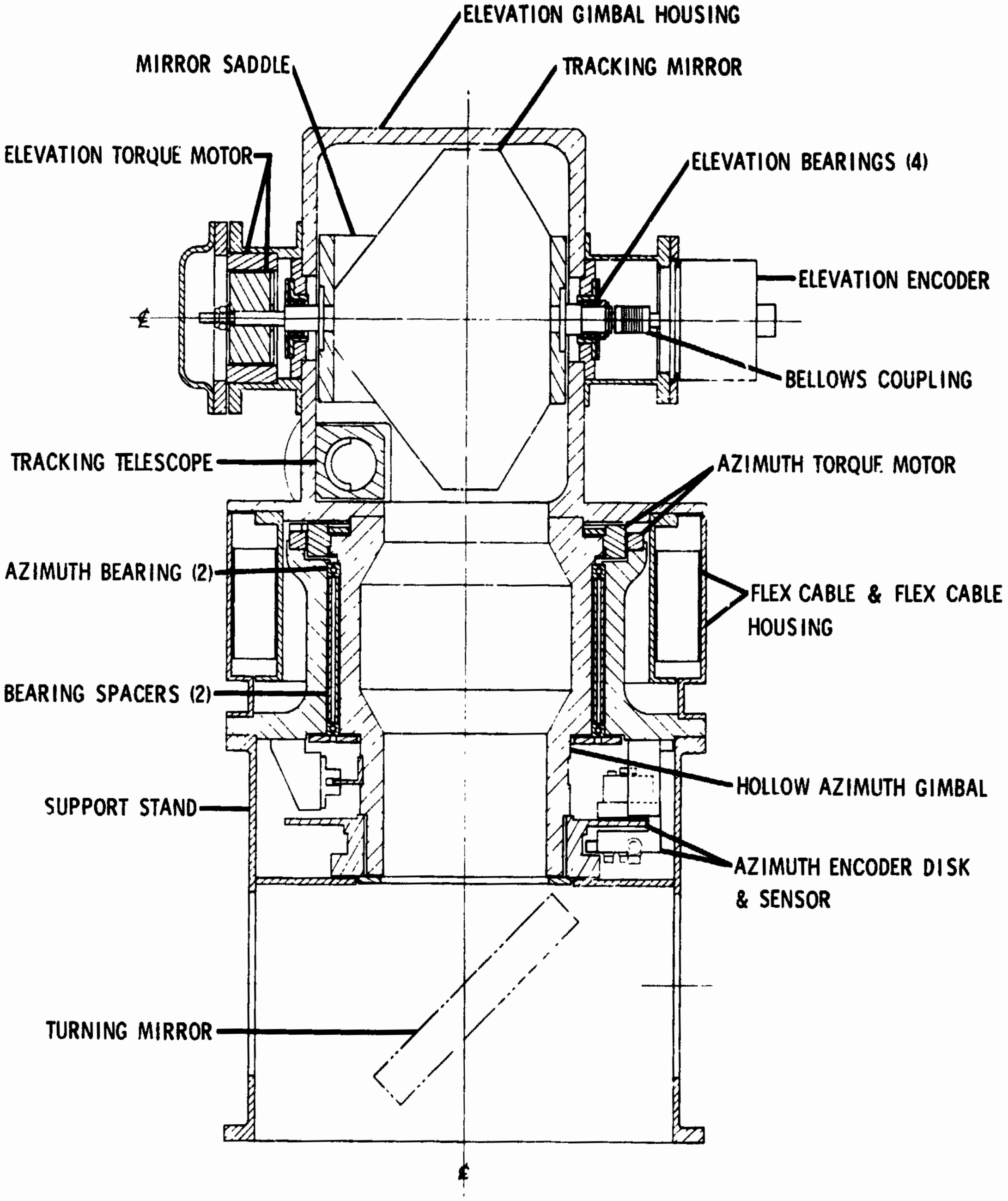


Figure 1. Solar Tracking Unit Assembly

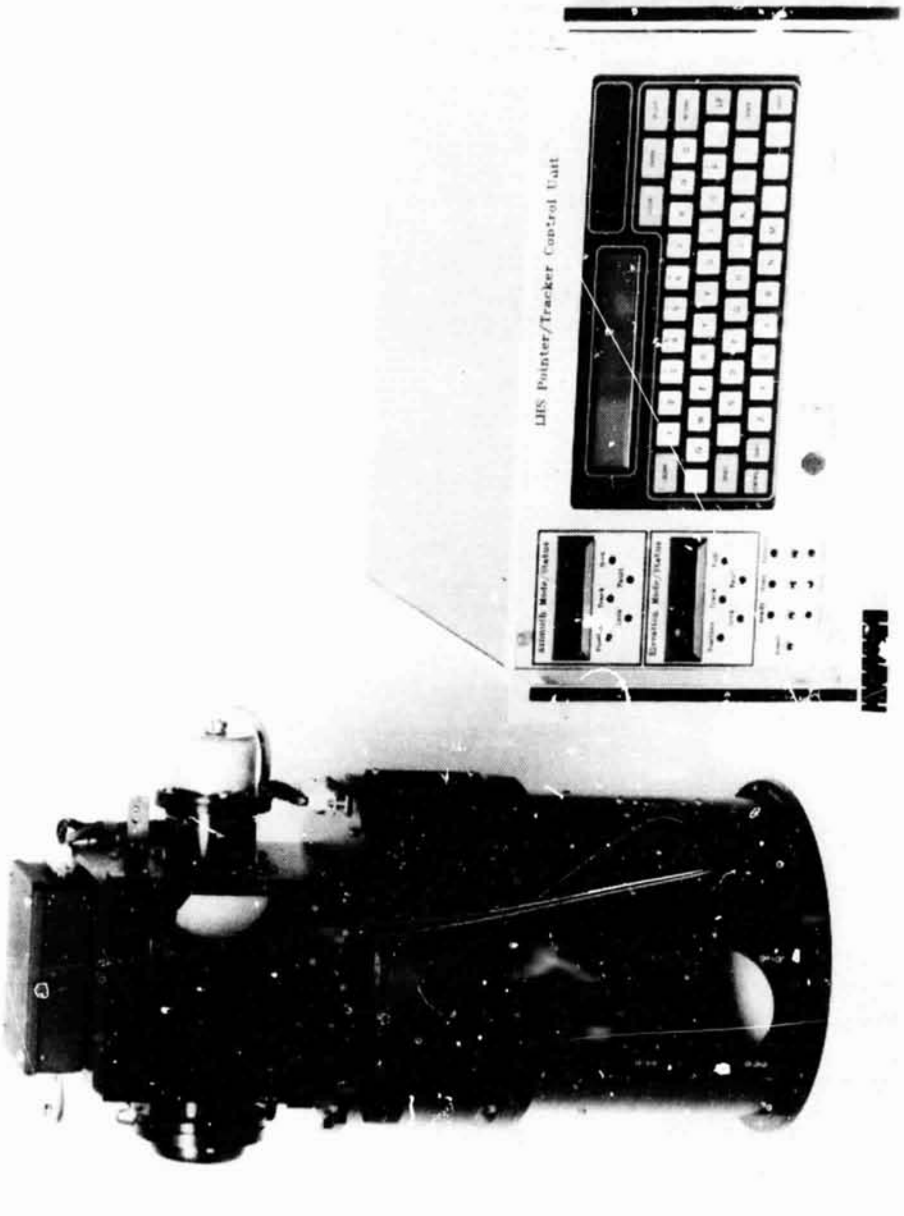
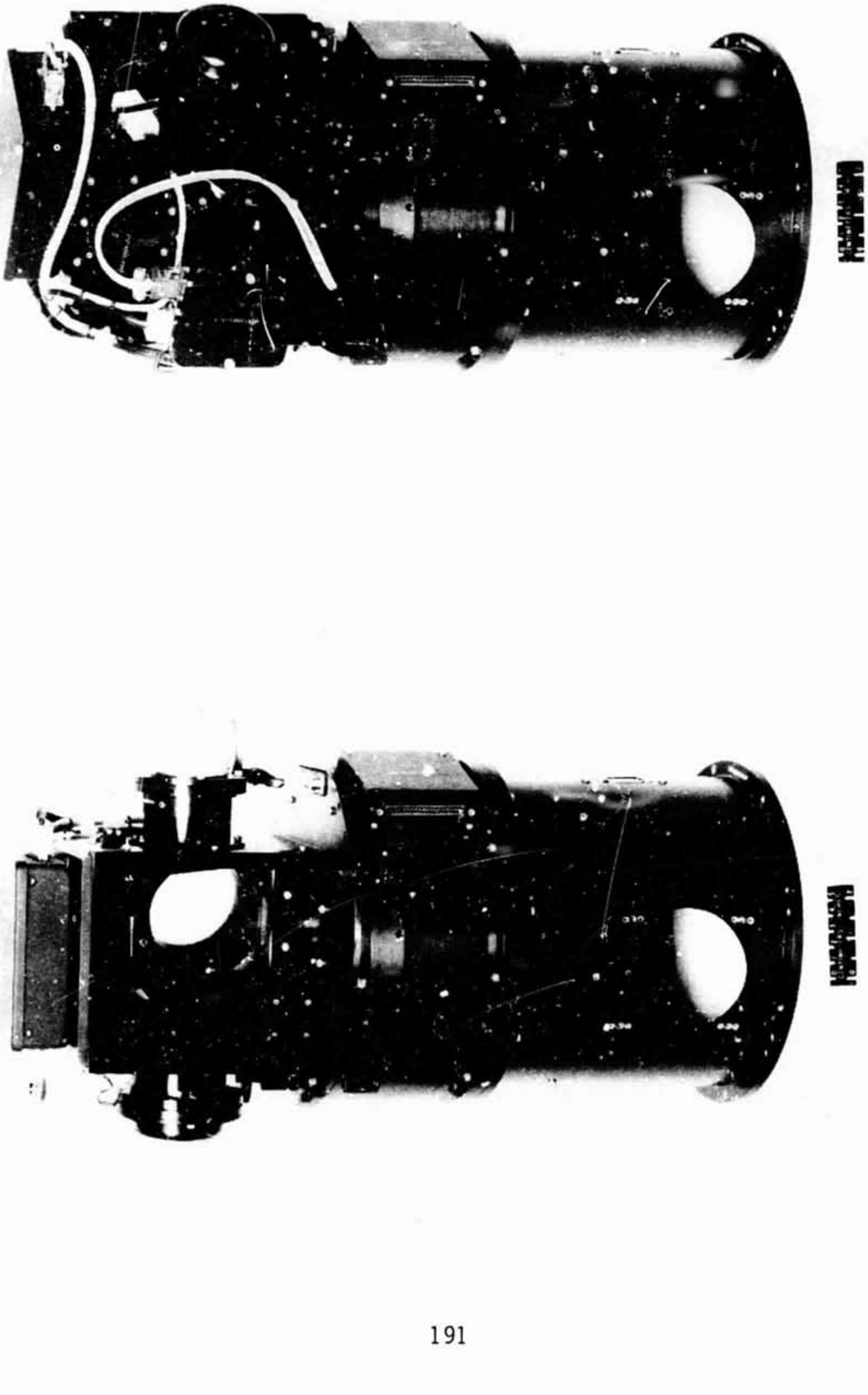


Figure 2. Solar Tracking Unit and Control Electronics



(a) (b)

Figure 3. Solar Tracking Unit

Elevation Gimbal

The elevation housing supports and protects the rotating mirror assembly and serves as a mount for the other elevation gimbal components. The housing itself is attached to the top of the rotating azimuth gimbal.

A saddle assembly, with removable shafts on each side, supports the Sun tracking mirror. The mirror consists of a nickel-plated aluminum body, coated on the front surface with enhanced aluminum for high reflectivity into the near-infrared spectrum. The elliptically shaped mirror is thick enough to be be self supporting and mounts to the saddle with three thin legs to minimize mirror distortion induced by the saddle. The shafts are supported by a pair of preloaded bearings mounted to the elevation housing.

The saddle and mirror are driven directly by a brushless dc torque motor. The stator of the component motor is mounted to the elevation housing and the rotor is mounted on one saddle shaft. A direct drive approach was chosen for its advantages over the use of gears. Direct drive gives a greater torque to inertia ratio, thus a higher acceleration capability. The lack of gear backlash gives maximum stiffness for a high-resonant frequency, and for high accuracy and resolution. An absolute angular encoder is attached to the other saddle shaft by a flexible bellows coupling. The encoder has a resolution of 0.33 arc-min, and is used as the position feedback for the control system.

The rotating components are balanced to better than the bearing friction torque: 0.00565 Nm (0.8 oz-in). The gimbal has an operating range of +25 degrees to -90 degrees with a manually lockable stow position at -90 degrees.

Azimuth Gimbal

The azimuth gimbal supports and rotates the elevation gimbal assembly and is mounted to the LHS instrument by a support stand. The hollow rotating part of the gimbal is supported by a pair of preloaded, large bore angular contact bearings. The thin-section, class 7 bearings have teflon separators for a low ratio of starting to running torque. The bearings are factory duplexed back-to-back for maximum structural stiffness, and are separated by a pair of equal length spacers.

The azimuth gimbal is driven directly by a commutated hollow bore dc torque motor. The armature of the component motor is mounted to the rotating, inner part of the gimbal and the field and brush assembly is mounted to the stationary part of the gimbal. The direct drive technique has the same advantages described for the elevation gimbal. A hollow bore incremental angular encoder with a resolution of 3.6 arc-seconds is used for position feedback to the control system. The rotating and stationary parts of the component encoder are carried by the azimuth gimbal in a manner similar to the torque motor.

The rotating components are balanced to better than the bearing friction torque: 0.0318 Nm (4.5 oz-in). The gimbal has an operating range of ±182°, with stops at each extreme and a manually lockable stow position at the nominal zero position.

Electrical power and signals are transferred through the azimuth gimbal to the elevation assembly by a flex-cable assembly. The flex-cable assembly consists of a loop of laminated flat conductor cable with one end attached to the inner housing and the other end attached to the outer housing (Figure 1). The outer cable housing is attached to the stationary part of the azimuth gimbal, and the inner cable housing is attached to the base of the elevation housing and rotates with the azimuth gimbal. The flat cable loop "walks" along the walls of the inner and outer housings as the azimuth gimbal rotates.

Tracking Sensor Telescope

The tracking sensor telescope, which is mounted in the elevation housing, contains the optics that form the Sun image on the tracking detector and an adjustable mounting system for the detector and preamp electronics. Figure 4 shows the telescope design. A diagonal mirror intercepts a portion of the sunbeam reflected down by the tracking mirror and directs it along the telescope axis. The beam energy is attenuated by a bandpass filter and neutral density filters to produce the desired level of energy on the detector. The filters are mounted in a removable holder which allows them to be changed without removing the telescope assembly from the elevation housing. An 80 mm (3.15 in) focal length lens forms an image of the Sun on the detector. The image size that is chosen provides a 2.0° telescope field of view.

When the telescope line of sight (LOS) is pointed directly at the Sun the image is centered on the four quadrants (active areas) of the detector as shown in Figure 5. If the image is not centered, there are differences between the detector quandrant outputs. These differences are combined to produce the error signals (Figure 6) that cause the tracking mirror gimbals to move and recenter the image on the detector.

The alignment of the tracking unit output beam to the LHS instrument optical axis depends upon the alignment of the telescope LOS to the true azimuth gimbal rotation axis. Any error in the parallelism of the telescope LOS with the azimuth gimbal axis results in a corresponding systematic tracking error as the azimuth gimbal rotates to follow the Sun. To accommodate manufacturing tolerances in the unit, an adjustment is provided to move the telescope LOS. The telescope is fixed to the elevation housing and the LOS is moved by translating the detector assembly in the focal plane of the lens. A compact mechanism in the telescope end produces a ±1.8° movement in LOS by translating the detector/preamp assembly in the two orthogonal directions corresponding to the directions the Sun image moves when the elevation and azimuth gimbals are rotated. In addition to the translation adjustments, a rotation adjustment for the detector/preamp assembly of ±2.5° is included to null the interaction between elevation and azimuth error signals.

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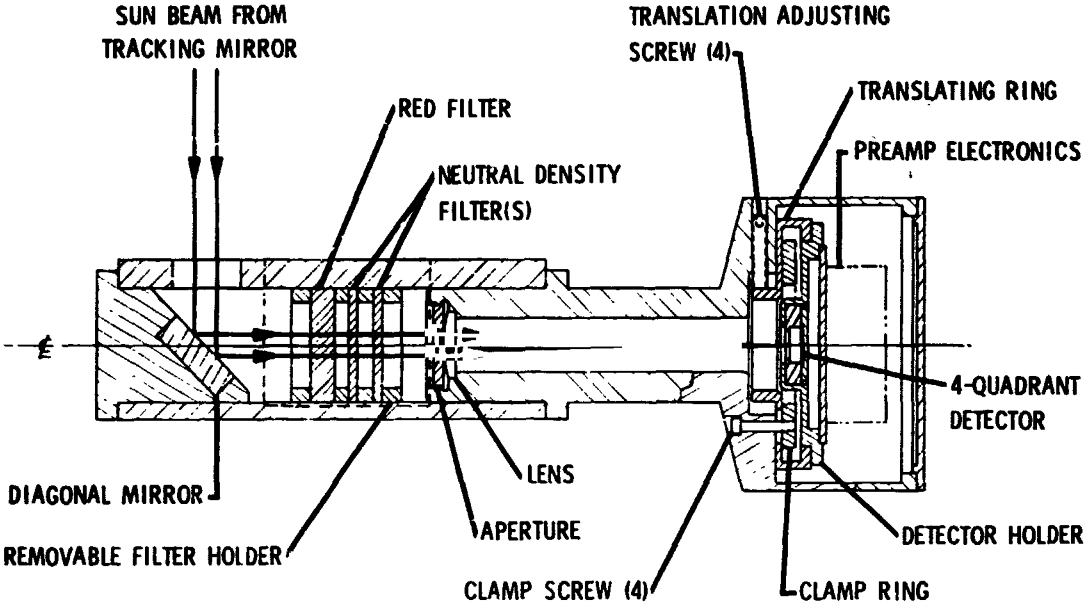

Figure 4. Tracking Sensor Telescope Assembly

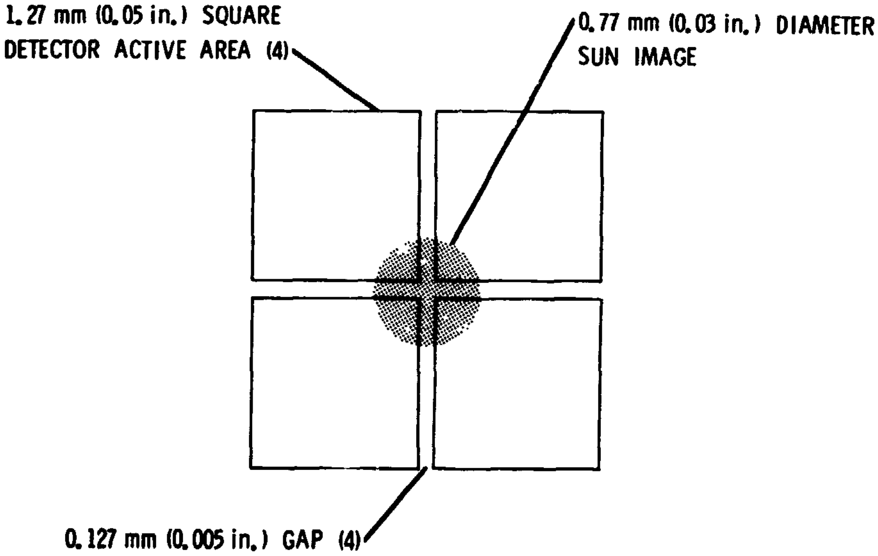

Figure 5. Sun Image on Detector

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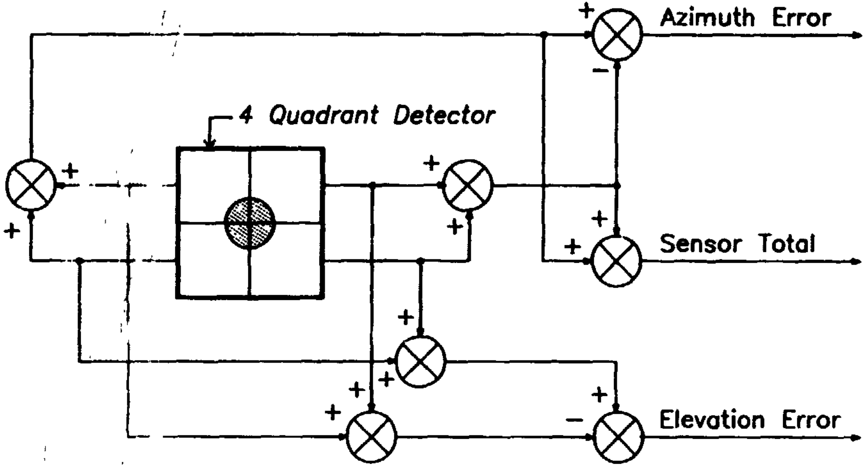

Figure 6. Sensor Error Signal Processing

CONTROL SYSTEM DESIGN

Control of Sun tracker gimbal motions is achieved by the azimuth and elevation servos operating under the control of the system microcomputer. The azimuth and elevation drive mechanisms are similar closed loop servos consisting of the gimbals, motors, encoders, tracking sensor, and the control unit. The control system electronics are composed of modular subassemblies which can be replaced with minimum impact on the system (Figure 7). The control unit contains the microcomputer, servo electronics, interfaces, controls, indicators and power supplies required for system operation. The remaining modular electronic assemblies are mounted on the gimbal assembly.

The servos operate in two basic modes: position and track. In Position Mode the gimbals are controlled relative to the internal coordinate axes of the unit by error signals generated from encoder outputs. In Track Mode the servos respond to error signals from the Sun sensor. Mode selection is achieved by analog switch closures under the control of the microcomputer. All operations of the Sun tracker consist of a sequence of these modes, commanded by the microcomputer.

The design of the control electronics and microprocessor software simplifies normal operation by providing preprogrammed, complex operational and self test features which can be activated by simple commands or switch closures. An extended command set provides access to lower levels of system operation to permit testing, fault isolation, normal operating mode modification, or alternate operating modes.

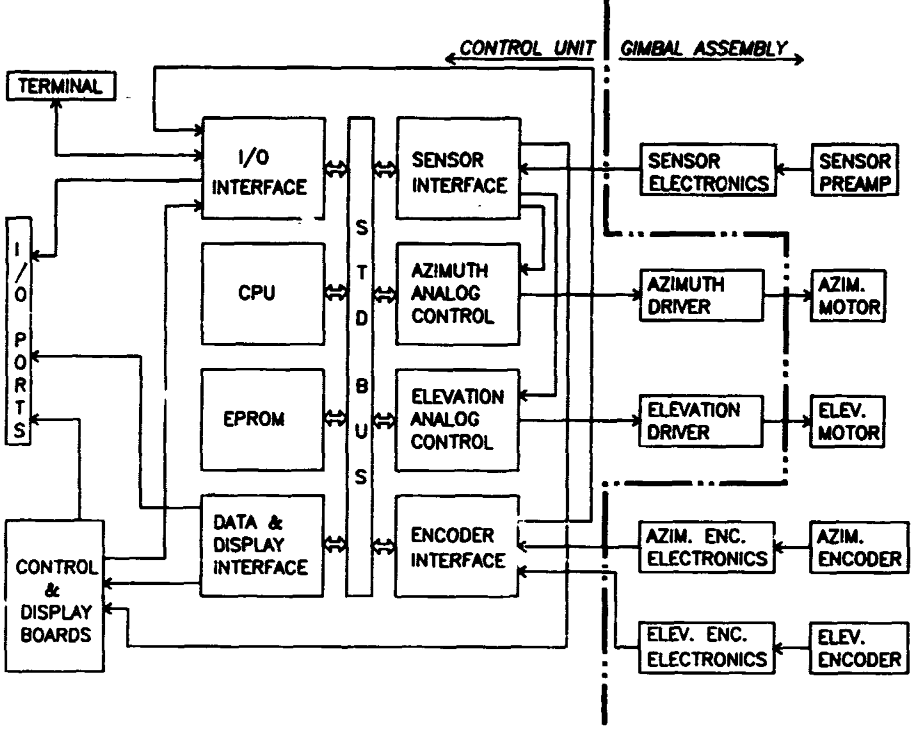

Figure 7. Control System Electronics Modular Interface Design

Servo Design

The elevation and azimuth servos (Figure 8) are similar in design and function so only the azimuth loop will be discussed; however, the differences between the servos will be noted.

Because the azimuth encoder is an incremental type, it requires initialization and a counter to accumulate the angular position information. Initialization of the azimuth encoder/counter occurs during system initialization and is updated (if necessary) every time the gimbal passes through the "zero" degree position. The angular position of the gimbal is provided to the microcomputer at a 1.5-kHz rate by the encoder interface module. In Position Mode the microcomputer uses the accumulated angular position in conjunction with a stored value, representing the desired position, to create position error. Position error is summed with velocity feedback derived by calculating the angular change occurring between the regularly sampled gimbal positions. The resulting error value is converted to an analog voltage by the D/A converter on the analog control module, amplified, and fed through the closed position mode switch. The amplified position error voltage is fed to the analog lead-lag compensation/switched integrator network which was designed to provide the desired closed loop response of the gimbal. The compensated error voltage is converted to a proportional motor current in the current driver module. The motor drives the gimbal to the desired position.

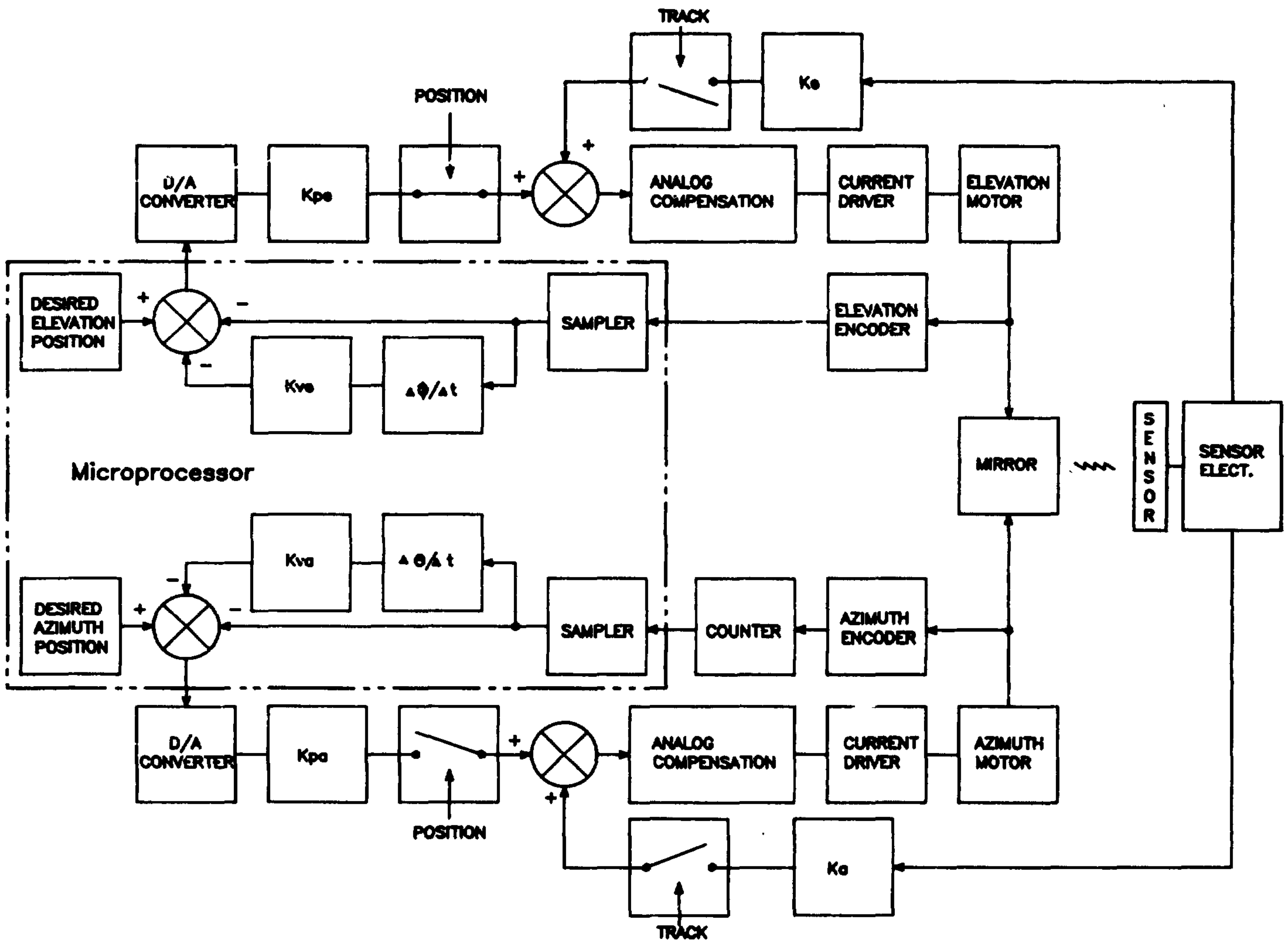

Figure 8. Servo Block Diagram

Because the elevation gimbal has an absolute encoder, the angular position is available from the time power is applied; no counter or initialization is required. The compensation and current drivers have the same form in elevation and azimuth, except for the selection of components and jumpers. The elevation motor is a wide angle brushless dc torquer. This device has a very flat torque response over an angle of approximately 60°, however, its operation is restricted to 120°. This motor is ideal for the elevation gimbal as the angle doubling effect of the elevation mirror makes smooth, ripple free motor operation essential, and only limited angular motion is required.

Although position information is available to the microcomputer in Track Mode, it is not processed to produce error signals, but is used in the fault mode detection logic. The track error signals are produced in the sensor electronics by combining the preamplified four quadrant outputs of the Sun sensor. The elevation and azimuth track error signals are then fed through the closed track mode switch on the appropriate analog control module. These error signals are processed the same as in Position Mode by the analog compensation, current driver, and motor except that they drive the gimbal to maintain the Sun image at the center of the four-quadrant detector.

Sensor Signal Processing

Three signals are produced by the sensor electronics module: elevation error, azimuth error, and sensor total (Figure 6). These signals are fed to the sensor interface module in the control unit where they are amplified by three ganged programmable gain amplifiers. The sensor total signal is converted to a digital value by the A/D converter on the sensor interface module by command of the microcomputer. The system has two uses for the value of the sensor total signal. During Sun acquisition, the programmable gain amplifiers are set to a fixed gain and the sensor total value is compared with a nominal one-half Sun value to determine if the Sun is located within the sensor field of view. The angular response of the four-quadrant sensor is dependent upon the intensity of incident energy. During track, when the automatic gain control (AGC) is enabled, the sensor total value is compared to a design value (representing a nominal one Sun intensity) and the gain of the programmable gain amplifiers is adjusted to maintain the sensor total at the design value. This is required to maintain nominal performance of the servos as the solar energy passes through greater or lesser depth of atmosphere and for ground operation where significant variations of solar energy occur with season, weather, and time of day.

DEVELOPMENT PROBLEMS

Tracking mirror balance

The location of the tracking mirror reflecting surface relative to the elevation gimbal axis had to be changed from the original design to bring the rotating mirror assembly into static balance. The original design, which placed the reflecting surface at the intersection of the elevation gimbal axis and the azimuth gimbal axis, with the mirror body and saddle located on one side of the axis, required a counterweight to balance the assembly. When the mirror design was completed, the rotary inertia of the mirror/counterweight combination was unacceptably large. The mirror position relative to the elevation gimbal axis was shifted forward to produce a balanced, minimum inertia, rotating assembly which required no counterweight. The final mirror position results in a loss of 17° in elevation LOS capability in the tracking unit, but the remaining range of +13° to -15° is adequate for the LHS instrument.

Azimuth bearing preload

The minimum design value of azimuth bearing preload was one-third the load supported by the bearings: 31 N (7 lb). The installed preload was to be set as closely as possible to this value to minimize starting friction torque. The bearings have a nominal, factory-set preload of 67 N (15 lb) when clamped together, but in the tracker they are separated by a pair of equal length spacers. Spacer fabrication was complicated by the fact that a spacer length mismatch of 0.0011 mm (0.000045 in) could result in a preload variation of 89 N (20 lb). The spacers were fabricated to a length mismatch of 0.0127 mm (0.0005 in). The bearing friction torque corresponding to the design preload was calculated from starting friction versus bearing preload data supplied by the manufacturer. During assembly, the load applied by the inner and outer bearing retaining rings was adjusted to compress the spacers differentially, until the desired starting friction was obtained.

Azimuth axis balance

The azimuth rotating assembly, which includes the complete elevation assembly, was not computer modeled and last minute design changes made the preliminary balance estimations inaccurate. Final balance could only be achieved by removing weight from the elevation housing and using a counterweight mounted to the inner flex cable housing. Space in the housing was critical, so a computer program was employed to calculate the counterweight shape and its location.

Removable neutral density filters

During testing of the tracking unit, conducted after the final alignment of the output beam to the azimuth gimbal axis, an increase in misalignment of almost one arc-minute was sometimes noticed if the filters were changed. The filters may have been refracting the sunlight, and this beam deflection changed the telescope LOS, and thereby, the output beam alignment with the azimuth gimbal axis. The substitution of an iris diaphragm, a nonrefractive element, for the filters would probably have eliminated this misalignment problem. The tracking unit telescope design was not changed, however, because the alignment shift did not affect the operation.

Soft stops to limit gimbal travel

The gimbal soft stops that were incorporated into the design did not pose a problem; however these stops are discussed because they eased the control system development task. Hard stops in the form of an arm contacting a pin were first considered, but soft stops were chosen to limit the structural and bearing loads during the gimbal deceleration. The stops consist of an arm that contacts and compresses a spring loaded plunger. The azimuth stop has a four degree deadband to permit a gimbal travel of ±182°.

The soft stops proved valuable during the initial control system checkout and testing. Software or hardware errors which caused the gimbal to be driven into the stops caused no damage, and checkout and testing were not restricted by such concerns.

Gimbal Servo Bandwidth

The design objectives included a 100 Hz bandwidth goal for the elevation gimbal control system, which would place it well above the 25 Hz bandwidth goal of the azimuth gimbal. Mechanical design considerations forced the mirror rotary inertia to increase substantially over the original design projections, precluding the possibility of achieving the desired goal. The reduced elevation bandwidth is approximately 50 Hz, which is satisfactory to achieve the tracking requirements. Testing has not shown any significant cross-coupling of motion between the azimuth and elevation gimbals.

TESTING

Because only one solar tracking unit was to be fabricated, all mechanical and electrical subsystems and modules were tested at the lowest possible level. This testing plan served three purposes: established baseline operation of each subsystem, improved the control system modeling, and provided early detection of anomalies. The major subassembly integration and test plan is outlined in Figure 9.

CONCLUSIONS

A solar tracking unit was developed which met or exceeded the LHS research instrument requirements. The unit has demonstrated a tracking stability and repeatability better than ±1 arc-minute. This unit, designed for use with the LHS instrument in an aircraft environment, could be adapted for use with other similar instruments or applications.

ACKNOWLEDGMENT

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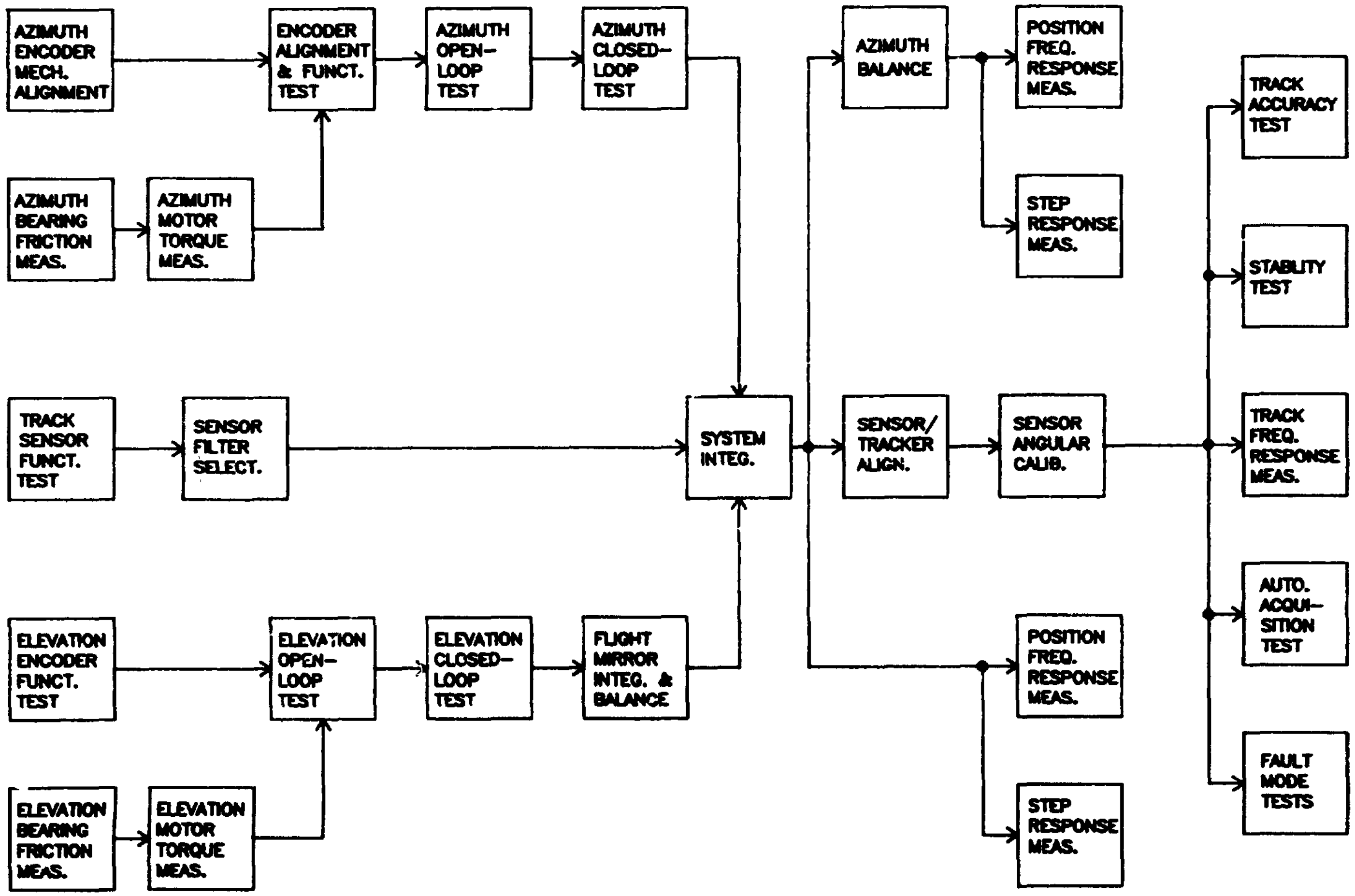

Figure 9. Major Subassembly Integration and Test Plan