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R. A. Deters
ITT Federal Laboratories

D. F. Eisenhut
ITT Federal Laboratories

R. F. Gates
ITT Federal Laboratories

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THE FINE GUIDANCE SENSOR,
AN ELECTRONIC SCANNING STAR TRACKER

R. A. Deters, D. F. Eisenhut, R. F. Gates
ITT Federal Laboratories
San Fernando, California

Abstract

The advent of space exploration has placed hitherto unheard of requirements on accuracy and precision sensing devices for guidance and attitude control. The necessity for high reliability, due to non-repairability, required new approaches to this design problem. Rather than try to improve upon existing systems, components, and approaches, a totally new concept evolved which eliminates the mechanical rotors and reticles of yesterday. Instead, a totally new breed of electronic scanning star sensor resulted.

This paper describes one such device, a Boresighted Star and Planet Tracker developed for precise attitude sensing and control of an experimental sounding rocket.

Discussed are the major elements of the basic sensing system, optics, detector, and electronics. The heart of the new sensor is the electronic scanning multiplier phototube, a small, rugged, highly accurate and highly reliable device. Electronic circuit design to enhance accuracy and precision is outlined.

Summary

The Fine Guidance Error Sensor (FGES) is a Boresighted Star and Planet Tracker developed for use as an error sensor for the Fine Attitude Control System (FACS) under development for the Aerobee 150-A sounding rocket program. The FACS is to operate in conjunction with the presently developed Inertial Attitude Control System (IACS). The IACS is used to despin the rocket after launch, and to point the rocket, including the tracker and experimental package, to within 4 degrees of a desired star. The tracker then acquires the target and provides error signals for the FACS to point the rocket within 30 arc seconds of the star. During the 3-5 minute period above the atmosphere, several successive stars can be tracked and studied.

The FGES is rigidly mounted to a scientific experiment which, in turn, is rigidly mounted within the nose cone. The tracker is boresighted with the experiment so that they point in the same direction. In addition to the two-axes error signals, several signals are provided for telemetry purposes.

The tracker has two modes of operation, an acquisition or coarse sensing mode covering an 8 degree diameter field of view centered on the boresight axis, and a tracking or fine sensing mode, in which the field of view is approximately 16 arc minutes. In the tracking mode, error signals with a resolution of 12 arc seconds RMS on a third magnitude AO star are provided in two axes. A unique feature of the tracker is its ability to scan a large field of view, select the brightest star, switch to a much smaller field of view, and provide

position information of excellent resolution on the selected star.

The basic star sensor consists of an optical lens, photo sensor, and electronics. The lens system gathers, and brings to focus, stellar radiant energy at the photocathode of a multiplier phototube, the heart of the system. The multiplier phototube has a photocathode surface which forms an electron image of the focused star image. It is constructed such, that when an accelerating voltage is applied between the photocathode and an internal mechanical limiting aperture, only electrons from a particular area of the photocathode will pass through the limiting aperture. This particular area is called the Instantaneous Photocathode Area (IPA). The IPA, when projected through the sensor lens, represents a region in space defined as the Instantaneous Field of View. Following the aperture is a secondary emission dynode structure providing signal amplification of approximately 10^7.

To utilize the tube in a star tracker system, a deflection coil is positioned around the multiplier phototube image section to provide deflection of the electron image. By applying the proper deflection currents, the electron image can be swept across the limiting aperture causing intensity modulation of the signal. Mode control logic locks the tracker operation into the search mode at turn-on. An acquisition field is swept in 16 arc minute segments at a rate of 6400 cps. Line rate is 200 cps and frame rate is 6.25 cps. Upon receipt of a tracking signal from the control system, a five frame star selection cycle is initiated. In this interval, star selection circuits set a reference level which selects only the largest signal present in the field. At the end of this time, the acquisition scan stops when the brightest star enters the Instantaneous Field of View and the tracking mode of operation is initiated.

In the tracking mode, a cross-scan sweep causing pulse position and pulse duration modulation of the electron beam is employed. Demodulator circuits develop an analog error which is used to control the DC deflection coil currents such that the cross scan is centered on the star image. The coil current magnitude is sampled and provides the output error voltages. As the vehicle control system responds to these errors, the tracking circuits constantly correct the DC coil currents to keep the cross scan centered on the star image.

The vehicle control system drives the vehicle so that the star is within the experimenter field of view. Following experiment time, the IACS slews the vehicle (and the tracker) to view another area. For correct star selection, the tracker is commanded to the search mode during the slewing operation. If not, since it had been tracking, it would continue to track the initial star until certain circuits saturated (up to possibly 6 degrees

from the initial boresight axis). Therefore, if the new area were less than 6 degrees from the initial boresight axis, a selection would not be made and the initial star would still be tracked. System operation is such that star selection takes place only in the search mode. Once a star has been selected, it will be tracked even if a brighter target should move into the search field of view. However, the search mode can again be initiated on command to select and track the brighter star. Table I is the summary of the tracker Performance Parameters.

Principles of Operation

The FGES provides two analog output error signals directly proportional to the angular displacement of the star, from each of two orthogonal planes whose intersection is the boresight or null axis of the sensor. Thus, when the star lies on this intersection, the output error signals are each zero.

Basically, the FGES is composed of the following:

(a) the lens system (for gathering and focusing radiant stellar energy on the detector)

(b) the detector (multiplier phototube)

(c) electronics

In the following, each of these items is covered in more or less detail. An overall Block Diagram is shown in Figure 1.

The Lens System

The lens system plays a major roll in determining the sensitivity and nulling accuracy of the FGES. However, this report is mainly concerned with electronic design. Therefore, the lens system is only briefly touched upon.

The lens aperture area determines the amount of radiant energy which is focused on the photocathode of the multiplier phototube, while the focal length of the lens system determines the angular Instantaneous Field of View.

Sensitivity. The photocathode current is determined by the following relationship:

$$Ip.c. = PAST$$

where S = sensitivity of photocathode in amperes/watt
P = power density at objective lens in watts/cm^2
A = clear aperture area in cm^2
T = transmission efficiency of lens system

Angular Field of View. The angular field of view is found by the following relationship:

$$A.F.V. = 2 \arctan \frac{dp}{2f_1}$$

where dp = diameter of Instantaneous Photocathode Area
f_1 = focal length of lens system

Multiplier Phototube

The heart of the FGES is the unique multiplier phototube developed by ITT. Basically, it is the result of the marriage of a standard ITT image tube and a standard ITT secondary emission multiplier stage. The MPT is constructed by replacing the phosphur in the image tube with a plate containing a small aperture and positioning the multiplier stages behind this aperture.

Now, as shown in Figure 2 , only electrons leaving the photocathode from a particular area will pass through the limiting aperture. This particular area is called the Instantaneous Photocathode Area (IPA), and the diameter of this area is 1.4 times the diameter of the limiting aperture. For instance, if the limiting aperture is 0.100 inches, then the I.P.D. is 0.140 inches.

Now, if a star is imaged by means of a lens system upon the photocathode, within the IPA, a very small stream of electrons will pass through the electron optics and through the limiting aperture. By placing deflection coils about the image section, it is possible to sweep this electron stream back and forth across the limiting aperture so that the stream of electrons is periodically interrupted, modulating the anode current.

Electronics

The tracker electronics can be broken into the following functions for more convenient explanation of operation:

(a) Mode Control Logic

(b) Search Scan Generator

(c) Track Scan Generator

(d) Video Amplifier and Star Selection Circuits

(e) Tracking Loop Control Circuits

(f) Output Error Amplifier

(g) Power Regulation and High Voltage Power Supply

Mode Control Logic. A detailed block diagram of the mode control logic is shown in Figure 3 . Four different logic levels are generated to control the tracker mode of operation. These are as follows:

$+S_A$ = Positive voltage level in search mode, zero in track mode.

$-S_A$ = Negative voltage level in search mode, zero in track mode.

$+S_T$ = Positive voltage level in track mode, zero in search mode.

$-S_T$ = Negative voltage level in track mode, zero in search mode.

The $-S_A$ and $-S_T$ levels are the two sides of a R-S flip-flop using PNP transistors. Two logic level inverter stages provide the $+S_A$ and $+S_T$ logic levels. The mode flip-flop is controlled by logic pulses from two groups of logic gates. An input from the Aerobee control system can effectively lock the system in the search mode by blocking the gate which allows switching to the track mode.

Assuming a command to track (control input becomes zero), the following sequence occurs. As no star presence signal is available, a clock pulse triggers a delay MSMV closing the gate and preventing switch to track for four raster scans. During this time interval the video amplifier and star selection circuits select the brightest star in the field of view. At the end of the delay MSMV time interval, an acquire MSMV with a single frame time gate interval is triggered. This monostable circuit prevents the tracker from returning to the search mode until a star presence signal has time to be generated after switchover to track. If no star video pulse has occurred during the acquire time interval, the entire cycle is started over.

Video pulses occurring during the acquire interval will cause the mode flip-flop to switch to the track mode. Sweep retrace blanking blocks any video occurring during sweep retrace. Should loss of signal occur during tracking, the loss of a star presence signal opens an AND gate allowing a clock pulse to return operation to the search mode.

Search Scan Generator. The raster scan of the search mode is a 32 step per line, 32 line per frame scan. Figure 4 indicates the generator components. A digital to analog converter forms the sweep waveform from a 10 stage binary counter chain. Clock pulses to the counter are fed through a diode AND gate which is closed stopping the scan wherever switchover to track occurs. The D-A converter drives the input current summing mode of an operational amplifier.

Track Scan Generator. The track mode cross scan waveforms as shown in Figure 5 are generated by the circuits of the block diagram in Figure 6.

Three flip-flops count down the 3200 cps pulses to provide timing gates. The 800 and 1600 cps flip flop outputs are combined in AND-OR gate circuits to provide an 800 cps squarewave shifted 90° with respect to the flip-flop 800 cps squarewave.

This phase shifted squarewave drives a Miller integrator to generate an 800 cps triangular sweep. The triangular waveform drives two bridge switches which are alternately gated on and off by the 400 cps flip flop outputs. The bridge switches are biased off by the mode logic during the search mode.

Video Amplifier and Star Selection Circuits. The video amplifier basically consists of a variable impedance input attenuator followed by a high gain amplifier

with a peak detecting star selection feedback network. The high gain amplifier output is fed to two separate fixed threshold output stages to develop the track and search mode outputs.

The input attenuator consists of a balanced diode attenuator network returned to the star selector. The attenuator, matched to the tube output through an emitter follower, drives an integrated circuit operational amplifier. A fixed clipping threshold is set by a zener diode network to allow only pulses exceeding a fixed amplitude to be amplified and used for star selection in the mode circuits. Discrimination of approximately one star magnitude is obtained.

Tracking Loop Circuits. A single channel of the tracking loop is shown in Figure 7. The error demodulators, which develop an analog error proportional to the star position from the center of the cross scan, function as follows. Diode AND gates use the 400 cps timing flip flop output to separate the video into pitch and yaw channel information. The 800 cps flip flop outputs separate the video into positive and negative scan information. Identical switches then drive a summing node to develop an error proportional to the difference between the positive and negative pulse widths.

The tracking integrators consist of a differential input stage and a dc coupled output stage. Capacitive feedback provides the integrator action. A shorting bridge on the output keeps the integrator from drifting during the search mode. The integrator output and the demodulator output are fed to opposite sides of the differential input of a summing amplifier along with the search scan. The amplifier is identical to the integrator design except that resistive feedback is employed. The summing amplifier outputs directly drive high impedance current drivers which are direct coupled to the deflection coils.

Voltage Regulators & High Voltage Power Supply. Power for the sensor is tapped from the FACS battery pack of +26 volts DC and -26 volts DC. Regulation to +20 VDC and -20VDC is provided by conventional voltage regulation circuits.

The high voltage necessary for the multiplier phototube is supplied by a DC to DC converter operating at approximately 3200 cps. This frequency provides synchronization for the complete system so the effect of switching spikes is minimized.

Output Error Generators. During tracking of a star, the coil currents consist of a DC component and cross-scan components. The error information required by the vehicle control system is proportional to the DC current component only. A filter combining low-pass and notch characteristics controls the system bandwidth and removes the cross scan current components. The error amplifiers are operational amplifiers especially designed for stability since they are outside the internal tracking loop and any drift at this point effects null accuracy directly. The error signal characteristics for either axis are shown in Figures 8 & 9.

The characteristics are valid for all angles in the opposite axis within ± 4 degrees of the boresight axis.

Sensor Configuration

Since all tracker operation is accomplished by electronic gimballing, there are no moving parts, within the system. Other than the phototube, all electronics are solid state. The housing has three individual chambers. An in-line lens system is used providing a minimum length of 10 inches. High component density module type construction as shown in Figure 10 is used for the electronics. Several of these cordwood modules make up each subsystem and are subsequently encapsulated in sealed cylindrical metal cans. The separate cans are required for signal isolation and ease of construction.

Mechanical adjustment of the tracker optical axis alignment with the mounting base is possible to within 15 arc seconds. In addition, electrical adjustment of this alignment is possible to within 5 arc seconds. The integral unit is sealed such that it can be pressurized for the experiment time.

Acknowledgement
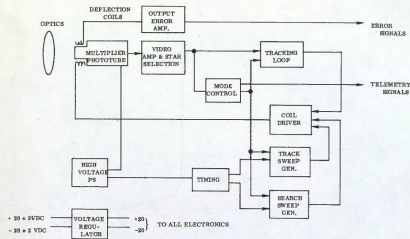
Figure 1. Basic Sensor Block Diagram
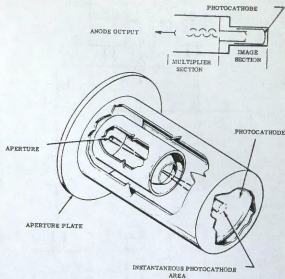
Figure 2   Multiplier Phototube
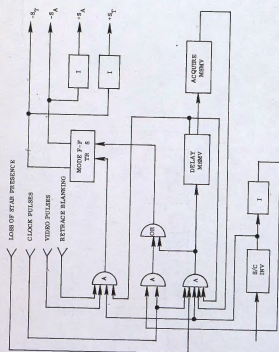
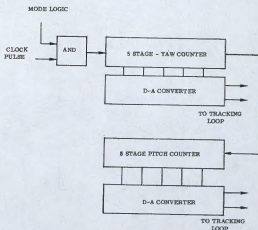Figure 3   Mode Control Circuits Block Diagram

Figure 4   Search Scan Generator
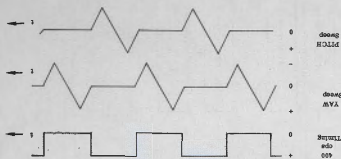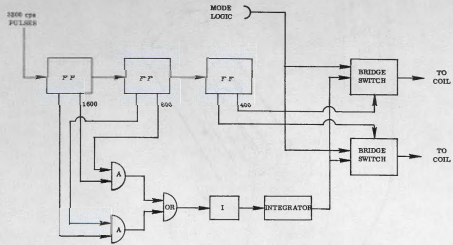
Figure 5   Track Scan Waveforms
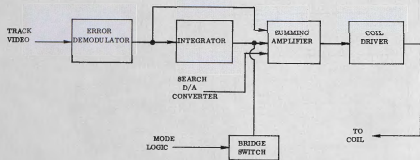

Figure 6   Track Sweep Generator
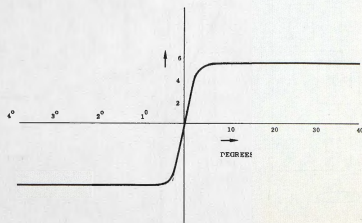

Figure 7   Single Channel Tracking Loop

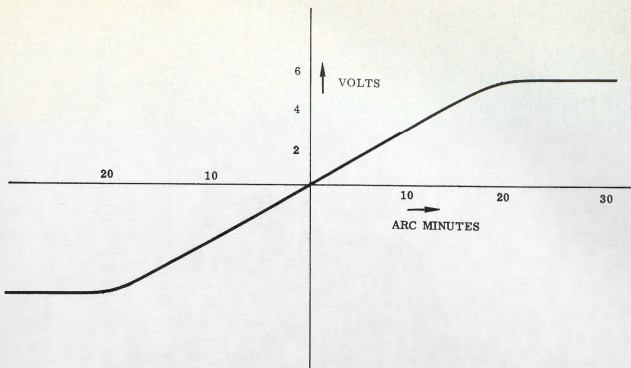Figure 8   Error Characteristic (Single Channel)

Figure 9   Error Voltage Characteristics
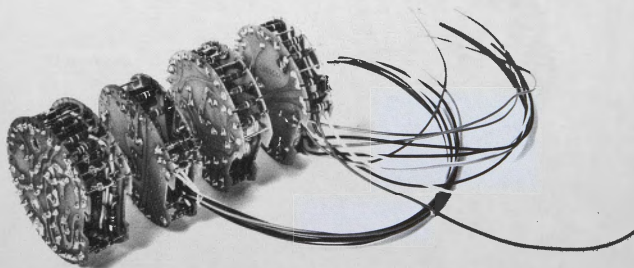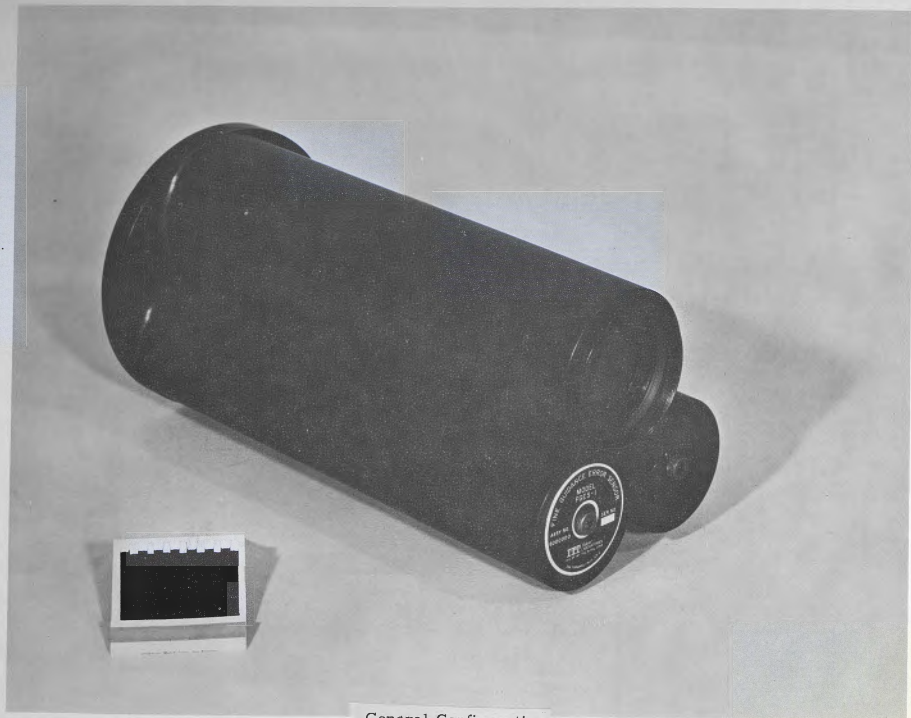(Expanded at Null)

Figure 10   Cordwood Modules

General Configuration
Aerobee Tracker