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BALLOON-BORNE ULTRAVIOLET STELLAR SPECTROMETER: ACQUISITION, TRACKING AND COMMAND SYSTEMS

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ABSTRACT

The NASA Balloon-borne Ultraviolet Stellar Spectrometer (BUSS) is carried to an altitude of 40 km by a 15 million cubic foot (4.25×10^5 M^3) balloon for night-time observations of ultraviolet stellar spectra. The BUSS optical system, comprising an 0.40 m aperture Cassegrain telescope and an Ebert-Fastie spectrometer, points at various selected stars and focuses a portion of their spectra on the photocathode of an image dissector tube. The spectral region between 2,775 Å and 2,825 Å is sampled by the detector at 0.25 Å increments using photon counting techniques. The pointing system for the payload uses a pair of orthogonal magnetometers which sense the earth's magnetic field for an azimuth reference, and a platform potentiometer for an elevation reference. This pointing system places the target star within the 3x1 degree field of view of an "outer" optical star tracker. The outer star tracker is then used to point the entire instrument to within one arc minute of the target star. Finally, an "inner" optical star tracker located near the focal plane of the telescope is used to tilt the secondary mirror sufficiently to bring the star image to within three arc seconds rms of the telescope's optical axis. The acquisition and tracking systems will be discussed as well as the design philosophy behind these systems and the p.c.m. digital command system. Actual performance figures from the June and October 1971 flights will be presented.

Since the development of reliable polyethylene balloons, astronomers have had available to them, at a moderate cost, a vehicle capable of carrying payloads of several hundred kilograms to altitudes from which observations could be made at wavelengths inaccessible to the groundbased observer. To the designer of such an airborne observatory, the problems associated with the pointing and stabilization of telescopes and detectors are formidable. Since each new experiment requires a unique set of pointing specifications, there is little standardization in either the design techniques or the hardware.

The performance requirements for the Balloon-borne Ultraviolet Stellar Spectrometer (BUSS) called for a balloon payload capable of acquiring and tracking at least five 5th magnitude stars during a night flight and recording their spectra in the range 2775-2825 Å with 1/2 Å resolution and with at least 10% counting statistics in each wavelength resolution element. Real time spectrometer data readout was also required to provide for increased flexibility in the observing program. An additional requirement was to have complete groundbased control of the pointing system and spectrometer to allow freedom of target selection at any time during the balloon flight. Due to physical size and environment

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dynamics, a multistage pointing concept was used. Detailed servo design information has been described by Gibson, et al (1972). The resulting hardware has been flown three times with successful results and, in general, all the design parameters and experiment requirements were met. The scientific results obtained from these flights have been reported by Kondo, et al (1972).

The payload is divided into two basic sections. The upper section is referred to as the pointed section and the lower section as the gondola (see Figure 1). The two sections are connected by a semi-rigid support shaft called the azimuth shaft, the upper end of which is connected to the balloon suspension train. The pointed section is mounted to the azimuth shaft by means of anti-friction load bearings. This section contains all the servo electronics, the PCM encoder, and serves as the experiment mount. The experiment is mounted in a cantilever fashion to a large flange on the end of a horizontal shaft/yoke fixture which is referred to as the elevation shaft. There is unlimited rotational freedom around the azimuth axis and 70 degrees around the elevation axis. The pointed section has attached to it a protective roll cage structure that prevents damage to it and the experiment in the event that the payload should turn over on landing. This structure also provides a means of mounting the magnetometer sensor block. The "roll cage" structure was fabricated from thin walled aluminum tubing and welded together in easily assembled sections. Electrical connections made from the gondola section to the pointed section are through a 14-segment brush and slip ring assembly. The gondola supplies power and pre-decoded command signals through the slip ring assembly and the pointed section supplies the PCM encoder output through the slip ring assembly to the RF transmitter located in the gondola.

The gondola section also serves as a reaction mass for the pointed section as well as the mounting area for the battery supply, command RF receiver and pre-decoder, RF telemetry transmitter, power control command circuitry, and balloon launch facility flight gear. In addition, a single centrally located ballast hopper and valve are mounted on the gondola. The ballast hopper is positioned directly in line with a vertical axis through the center of mass of the entire payload. This location reduces to negligible proportions the effect of induced forcing functions on the servo during ballasting operations required for balloon control.

The gondola is a truss structure fabricated from aluminum angle to reduce the cost of repair and refurbishment. Field damage is easily repairable since the damaged piece can simply be replaced with another which is cut and formed using common hand tools. The mass of the telescope, spectrometer, and associated equipment run about 91 kg, and the roll cage, about 58 kg. The mass of the entire pointed section, including all electronics, mechanical pointer structure, star trackers, and counterweights, is roughly 244 kg. The gondola, with batteries and NCAR equipment, has a mass of about 210 kg. To this is added whatever ballast is required by NCAR for flight operations.

Pointing is controlled in three separate stages. The first system, referred to as coarse acquisition, was designed to acquire the target to within the field of view of an "outer" star tracker by referencing to the horizontal component of the earth's magnetic field for an azimuth reference and to local horizontal via a potentiometer for an elevation reference. The second stage of pointing, referred to as the platform tracker loop, is
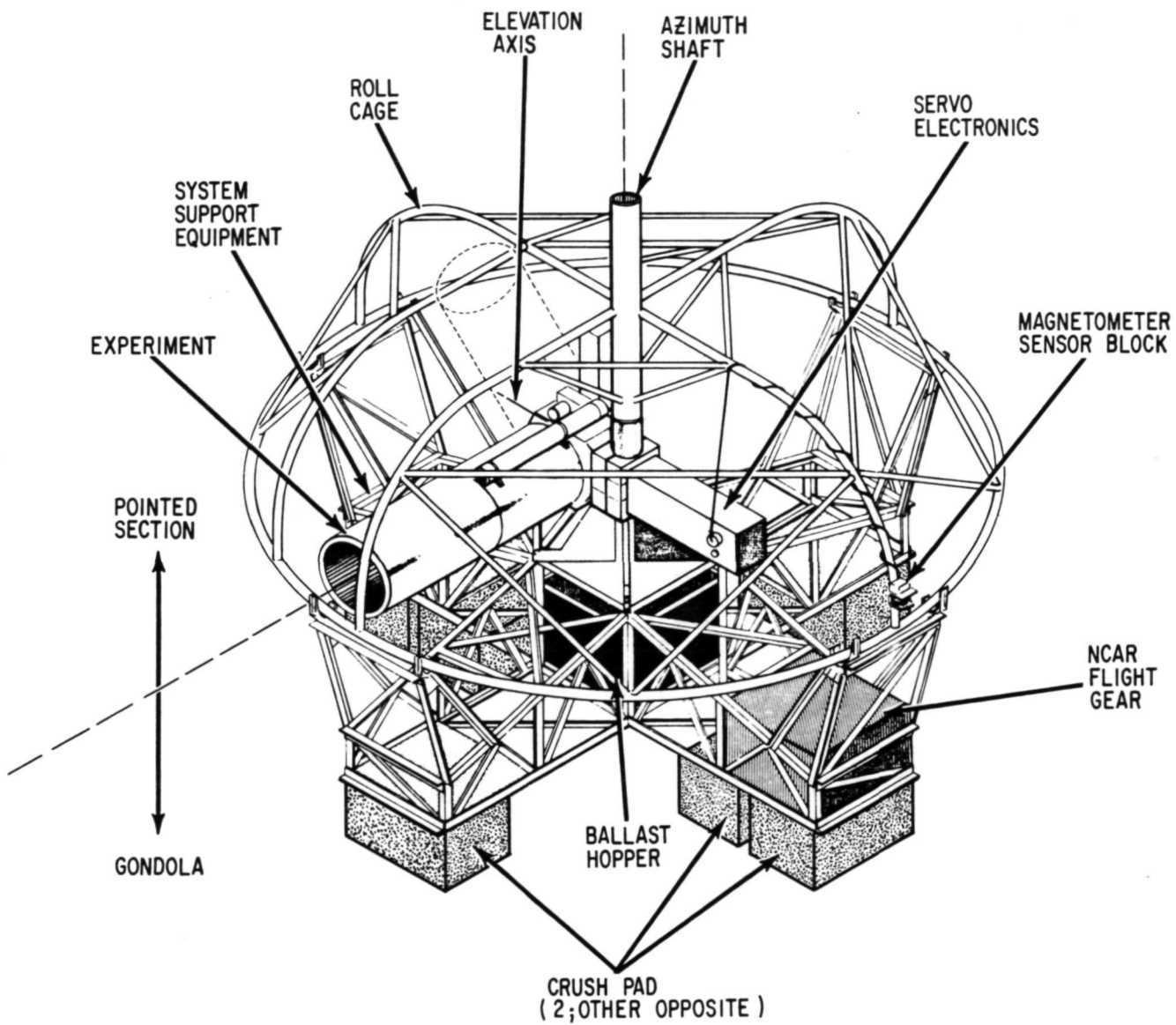
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Figure 1. BUSS Payload configuration.

controlled by the outer star tracker, which has a ±1.5 degree field of view in azimuth and a ±0.5 degree elevation. The tracker is bore-sighted to the optical axis of the telescope and will drive the control system to a null angle that is within 1-arc minute of the optical axis of the telescope. The third stage, called the inner loop, achieves very fine pointing with an "inner" star tracker located approximately at the focal plane of the telescope. Signals from this star tracker are used to drive two d-c torquers to tilt the secondary mirror about two orthogonal axes so that the off-axis star image is stabilized to within about 3-arc seconds rms of the optical axis. The ultimate accuracy of this loop is limited by the star tracker noise, which is itself a function of star brightness, and the velocity error constant of the control loop. Pointing commands and other operational mode commands are telemetered from the ground through a serial digital PCM command system.

The magnetometer selected for use on the outer acquisition loop is a Heliflux MND-52C-300NB, manufactured by the Schonstedt Instrument Company. The elevation potentiometer is a precision resistive film, one-turn type, manufactured by the Computer Instrument Corporation. As prime movers for both the azimuth and elevation axes, Inland Motor Company T-4036 d-c torquers were selected. The outer loop star tracker was designed and built by Ball Brothers. It was designed to track the brightest star in its field of view below the level set in the remotely set magnitude discriminator circuit.

The outer-loop azimuth control system is mechanized to stow the experiment platform to a potentiometer null referenced to the azimuth shaft. The stow drive is rate limited to approximately five to seven degrees per second. A balloon rotation of 1.0 degree per second can be easily handled in stow; however, acquisition time is increased.

A block diagram of the azimuth loop is shown in Figure 2. Azimuth acquisition of the three-degree target field is accomplished by commanding the experiment platform relative to the local north-south earth magnetic field line. Two horizontal orthogonal magnetometers are used to provide azimuth reference from magnetic north. The magnetometer control loop has a bandwidth of about 0.3 Hz and points the experiment to a stable null provided by the ground commanded angle and the sensed magnetometer angle. The servo loop is proportional plus "limited" integral, thus, no servo loop pointing error is evident for nominal friction torques of 1.7 lb-in. (.197NM). The integral term is limited to prevent poor performance during acquisition.

A target field 180 degrees away from magnetic north can be acquired in about 40 seconds. For the 180 degrees acquisition, rates of 20 degrees per second will occur. This high rate is produced because the rate limiting circuit does not prevent rate build up on the unstable null side during acquisition. For acquisitions of 90 degrees or less, the rate limit is about five to six degrees per second. Acquiring the target star 90 arc-minutes away from Star Tracker null takes approximately seven seconds.

The azimuth acquisition principle is based on generating the trigonometric identity:

$$\cos \Psi_A \sin \Psi_T - \sin \Psi_A \cos \Psi_T = \sin (\Psi_T - \Psi_A)$$

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where

$$\Psi_A = \text{magnetometer angle from magnetic north}$$

$$\Psi_T = \text{target angle from magnetic north}$$
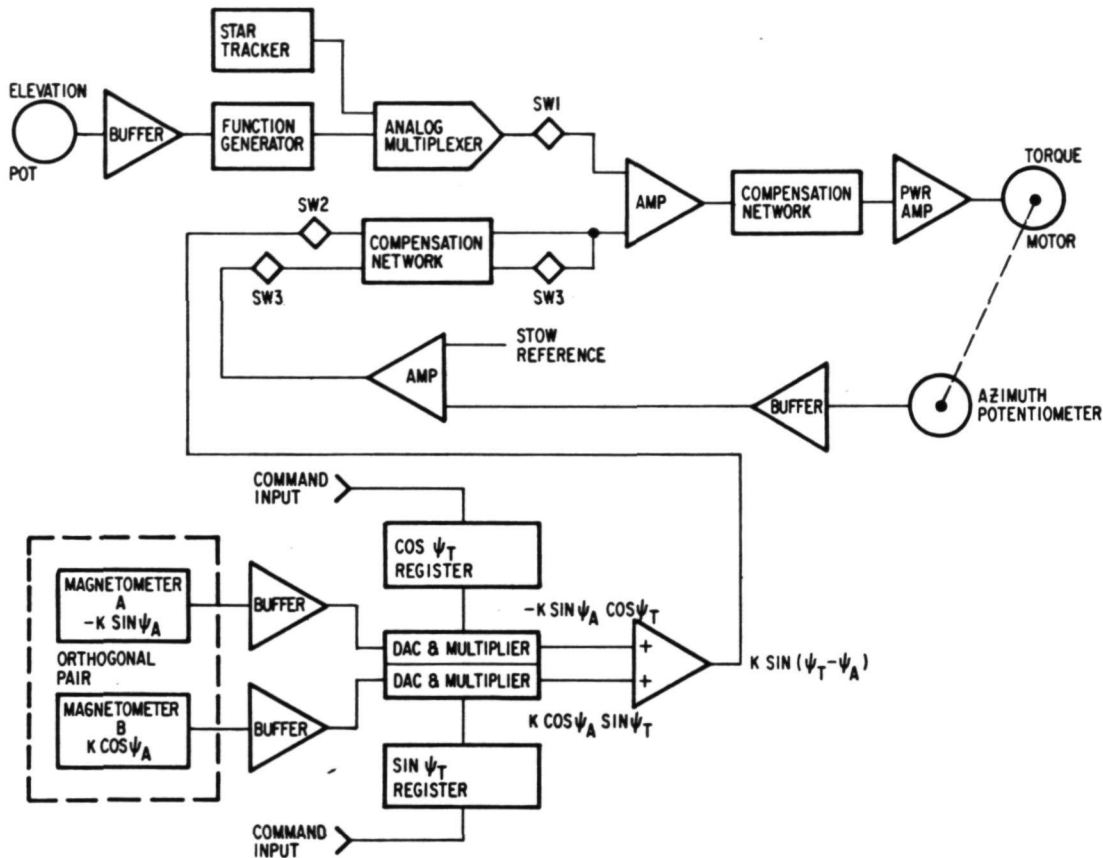
$$(\Psi_T \text{ is the commanded angle})$$

Figure 2.   BUSS Azimuth Servo Block Diagram

The azimuth Star Tracker signal is scaled in an analog multiplier by a scaler that is proportional to the elevation angle of the target. The scaling factor is:

$$S_F = K\text{Sec } \theta$$

where θ = angle above horizontal.

Scaling is necessary to maintain a reasonably constant servo gain, or otherwise, the effective gain of the azimuth servo will fall off as a function of the cosine of the elevation angle. Scaling of this nature will permit reliable operation up to at least a 70 degree elevation angle.

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The outer loop azimuth Star Tracker control system also uses a proportional plus limited integral technique. The "steady-state" pointing error is zero considering the friction torque effects and the integrator action. The azimuth Star Tracker loop has a bandwidth of roughly 0.5 Hz. Transient effects of direction changes for kinetic friction torque and signal noise from tracking targets of 0 to +5 visual magnitude result in less than 0.4 arc-minutes of experiment pointing error. Control bandwidth for this loop which is determined by loop gain and the compensation lead terms must be compromised with torque motor noise output. Battery stored electrical power is consumed proportional to motor noise. The resultant azimuth pointing accuracy is nominally less than 1.0 arc-minute.

A block diagram of the outer loop elevation control is shown in Figure 3.
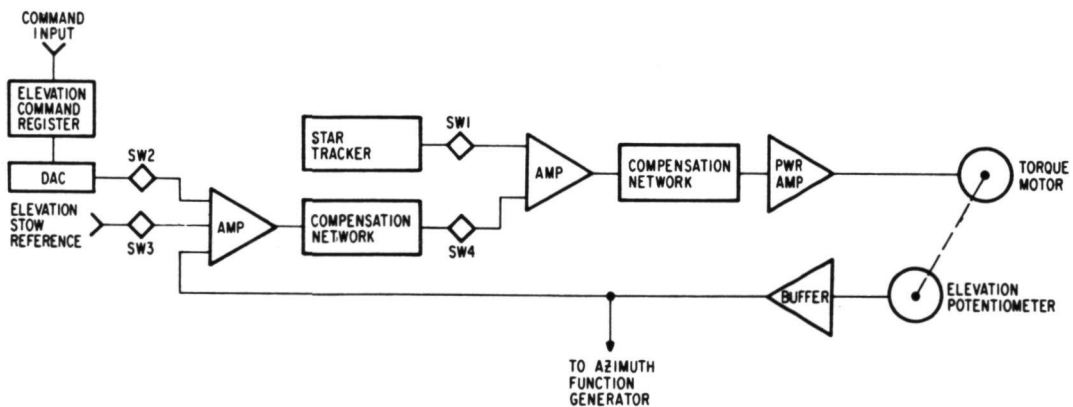
Figure 3.   BUSS Elevation Servo Block Diagram

Elevation control was designed to stow the experiment section and point the experiment to a 1.0-degree target field referenced to a potentiometer null. Potentiometer null was set normal to the azimuth shaft. The elevation servo was designed to handle an azimuth shaft oscillation at the simple pendulum frequency with an amplitude of plus and minus 1/3 of a degree. As in the azimuth control loops the elevation control is proportional plus limited integral. The limited integral "washes out" pointing errors in acquisition and track that result from the 1.27 lb-in. (0.144NM) kinetic friction torque

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and a maximum 3.0 lb-in. (0.34NM) torque of mass unbalance around the elevation axis. The elevation acquisition of a target field is rate limited at approximately eight degrees per second; thus, acquisition of a target field 70 degrees from start will require about ten seconds. Acquisition of the target star to within the 1.0 degree field of view will be less than eight seconds. Elevation tracker loop bandwidth is about 1.4 Hz. Again, the bandwidth is reduced to decrease torque motor power consumption while tracking the noisy signal from dim targets. Another reason for keeping bandwidth low was to reduce error rate inputs to the experiment section secondary mirror control system. The transient pointing errors in the elevation axis while tracking stars of 0 to +5 visual magnitude are less than 1.0 arc-minute.

Azimuth acquisition of the target star relies upon knowledge of (a) payload geographical position, (b) target ephemeris data, and (c) knowledge of the direction of the horizontal component of the earth's magnetic field. A computer program, derived from data supplied by the National Oceanographic and Atmospheric Association (NOAA), provided the means for determining the direction of the horizontal component of the earth's magnetic field to less than 0.5 degree. Use of the OMEGA system at the NCAR balloon facility in Palestine, Texas, produced geographical coordinates allowing for position determination to less than five miles. However, payload geographical position need only be known to approximately ten miles. Elevation acquisition of the target relies only upon knowing the geographical position of the payload and target ephemeris data. These data, when referenced to payload local vertical, provide the information needed to program a precision potentiometer in the elevation servo loop.

The graphs in Figure 4 are plots of the outer loop Star Tracker pointing error versus time. These data are taken from Flight 2 and are typical of inflight performance. Graphs A and B show initial Star Tracker acquisition in azimuth and elevation respectively. Note the moderately light damping used to permit sufficient gain to be used while pointing on target. Graphs C and D are again respectively azimuth and elevation Star Tracker pointing error versus time after acquisition stabilization. The predominant error appears at about a 0.6 Hz rate. The forcing function for the error input has as yet not been specifically identified. However, there is evidence to indicate a torsional oscillation of the 10-foot long section of the three-cable suspension train. Graphs E and F are examples of the worst case-pointing that occurred for relatively short time periods. The predominant motion is in azimuth and is probably a result of torsional suspension line energy coupling into the servo. This is being evaluated and will be corrected.

Once the outer loop controls have done their jobs and the stellar image is stabilized to within one arc minute of the outer loop tracker's null axis, the "inner loop" star tracker is activated. Telemetry signals from the inner loop tracker verify that the star tracker sees the target star and also give an indication of the apparent brightness of the star. There is no magnitude discriminator circuit in the inner loop tracker. The inner loop control system is an integral plus proportional, d.c. type 1 loop. Error signals from the tracker are processed by the compensation networks, amplified by the CTC model 916 100 watt servo amplifiers and applied to two d.c. torques to tilt the telescope's secondary mirror sufficiently to bring the star image to within approximately 3 arc seconds rms of the tracker's null axis.
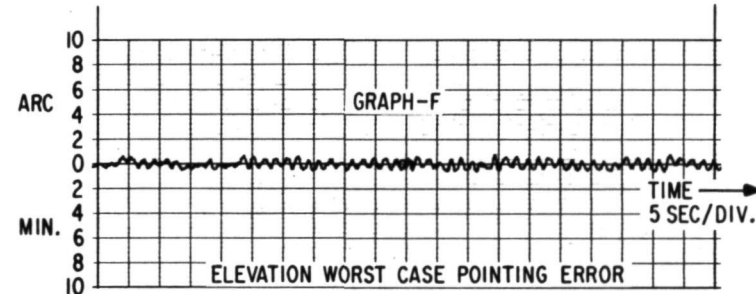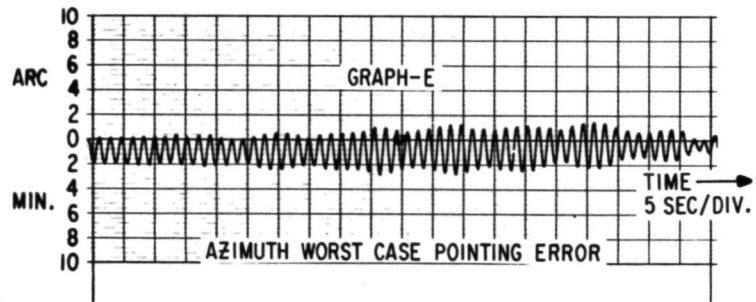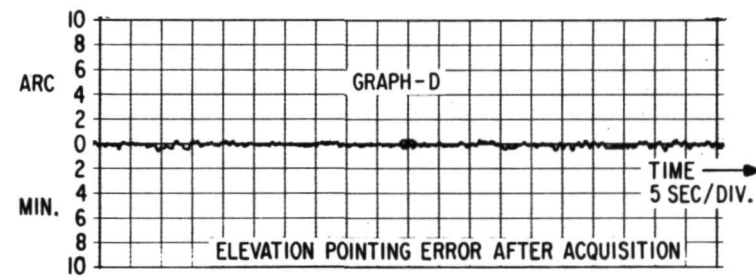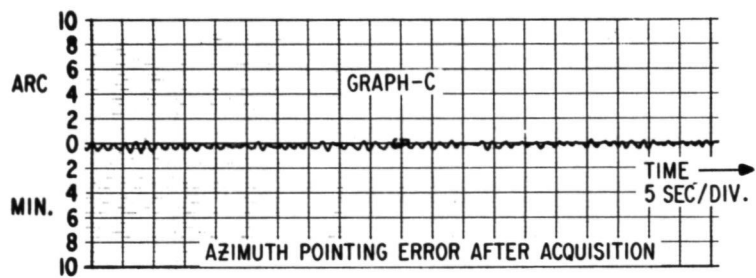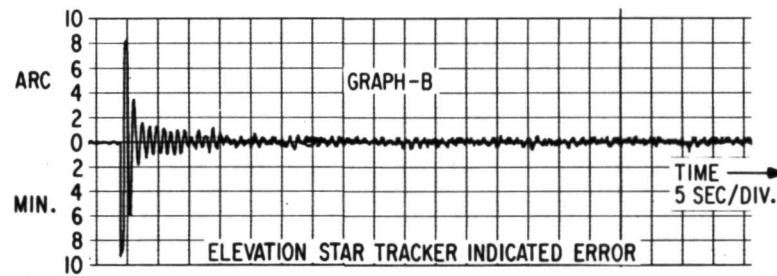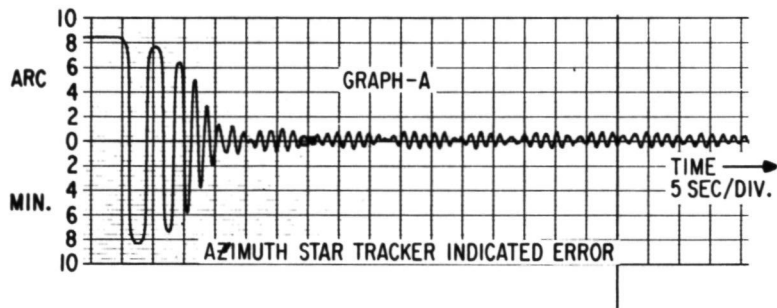
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Figure 4. Star Tracker pointing error data.

For the first two flights of the BUSS payload, an EMR 569B-M1 optical star tracker was used for the inner loop. During both flights there were irregularities with the performance of the sensor so that for the third flight a new star tracker was procured from Ball Brothers. The new tracker is in most ways a duplicate of the original outer loop tracker. The reader is directed to reference 1. (Gibson, et al, 1972) for a detailed discussion of the outer and inner loop control systems.

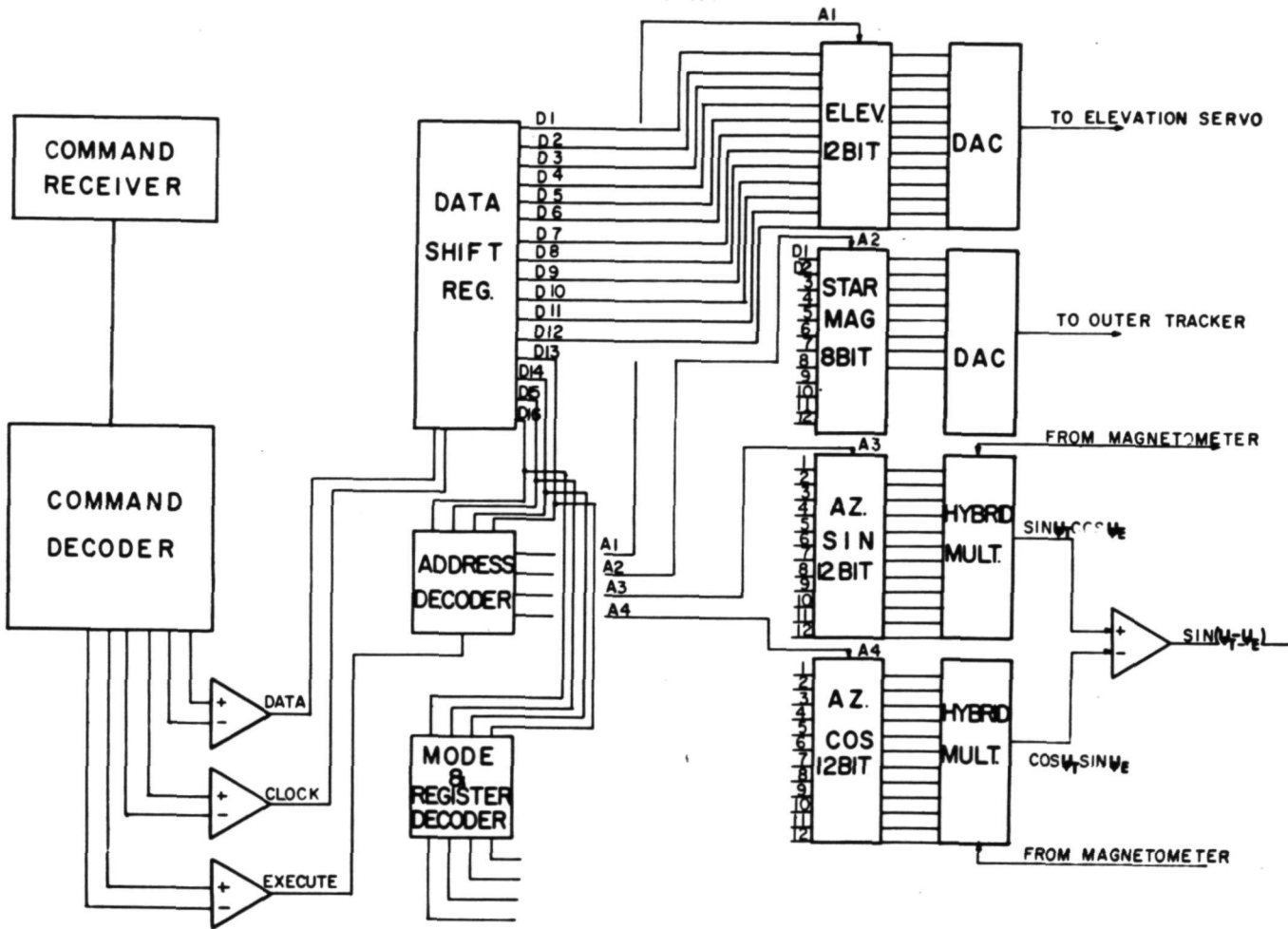A block diagram of the BUSS command system is shown in Figure 5.

Figure 5. BUSS Command System Block Diagram

The command system is a serial digital p.c.m. type. The decoder section has been recently redesigned because of a failure during the third flight. Commands are encoded on the ground by simply setting the positions of sixteen single pole double throw toggle switches to correspond to the states of the bits of the command word. The digital word thus derived is serialized and used to deviate a voltage controlled oscillator which in turn deviates a 430 MHz FM carrier for transmission to the payload. Each command word actually contains 23 bits. The six least significant bits form a fixed recognition pattern. The seventh bit is a sign flag to inform the airborne decoder whether the command word is an information or discrete type command. Discrete

commands are used for relay closures and other latching functions such as main payload power on and off.

In the ground station command encoder discrete commands are encoded by use of a two digit thumbwheel switch. This switch in turn produces a two decade BCD code corresponding to the decimal value set on the thumbwheel switch. If the thumbwheel is set to any number other than 32 the sixteen discrete switches on the front panel of the encoder have essentially no effect on the command, and the "tag bit" is encoded as a logic zero.

The video signal originating from the airborne command receiver, is routed to a pair of notch filters in the command decoder. These filters function as subcarrier discriminators and reconstruct the digital bit stream as encoded on the ground. The bit stream is then located in one of two twenty-three bit shift registers. The command decoder is designed to require that each command be received twice and that the two commands be identical before it is acted upon. As the second command is received the first command is shifted to a second shift register and the new command is then stored in the location just vacated. Magnitude comparator circuits then decide if the two commands are identical. If the two commands are identical, a routine is executed to multiplex the 16 bit word and transmit it through a line driver to the pointed section of the payload where it is executed. If the command is a discrete type it will trigger a 28 bolt, 500 ms pulse, on one of sixteen possible circuits depending on the position of the thumb-wheel switch mentioned above.

To turn main battery power on to the payload a separate battery power controller is used. The controller accepts the 28 volts, 500 ms pulse from the command decoder and employs it to trip a one shot multivibrator which in turn sets a J-K flip flop. The output of the flip flop is connected to a hybrid interface gate (Sprague UHP-503). When active, this circuit sinks enough base current from a PNP silicon darlington to saturate the transistor. In the saturated state, the 2N6050 acts as a switch between the payload's silver zinc batteries and the pointed section of the payload.

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REFERENCES

Gibson, W. C., et al., 1972. Pointing and Guidance of the BUSS Telescope. Proceedings of the Society of Photo-Optical Instrumentation Engineers. 28:249-260.

Kondo, Y., et al., 1972. Observations of the Stellar Mgx II Doublet at 2795Å and 2802Å. The Astrophysical Journal. 176:153-164.

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DISCUSSION SUMMARY — PAPER 4.3

In comparing the usefulness of this system with OAO the speaker noted that it operated near 2,000 angstroms which is not optimum for OAO.

Inquiries were made on several details of the pointing and stabilization system as summarized below:

Q. How well does the magnetic stabilization system point?

A. The magnetometer orientation must bring the object within a 3-degree field-of-view.

Q. How do you couple or decouple your cell to the balloon for pointing?

A. The instrument is mounted around the azimuth shaft. The shaft is connected onto the balloon suspension line. The coupling to the train is only through the slight friction in the bearings, so we simply react about the gondola and suspension line.