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A General-Purpose Balloon-Borne Pointing System for Solar Scientific Instruments

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I. INTRODUCTION

NASA is placing new emphasis on high-altitude research balloons because of their low-cost and quick-launch advantages over rockets, satellites, and the space shuttle [1]. Typically, research balloons can get scientific payloads to float at altitudes of 130,000 ft for hours or even days. This is satisfactory for a number of solar scientific instruments like the solar optical universal polarimeter (SOUP). The SOUP has been developed by the Lockheed Missiles and Space Company in Palo Alto, California, and is a candidate for balloon flight. It is an instrument that is approximately 6-ft long, 1.5 ft in diameter, and weighs about 400 lb. To meet its scientific objectives, it must be pointed at the Sun, stable to within 0.25 arc-min rms in pitch and yaw and 2 arc-min rms in roll.

This paper presents a general-purpose balloon-borne pointing system for accommodating solar scientific instruments like the SOUP. It is configured for precise pointing, low cost, quick launch, and for use by a wide variety of solar instruments. It offers the option of three-axis control, pitch-yaw-roll, or two-axis control, pitch-yaw, depending on the needs of the payload. This system is described in section II. Simulation results for it with the SOUP as the science instrument are given in section III, for both the three-axis and two-axis control options. Final comments are made in section IV.

II. DESCRIPTION OF THE POINTING SYSTEM

The general-purpose balloon-borne pointing system presented in this paper has most of its hardware on the gondola, to provide a quick-launch capability. There is a reaction wheel on the gondola for generating control torques in azimuth. There is a bearing and torque motor at the top of it that attaches to the flight train. The torque motor torques against the flight train to put low-frequency torques on the gondola in order to keep the reaction wheel speed from saturating. There are three silicon solar cells mounted 120 degrees apart around the azimuth axis of the gondola that are used in the initial Sun acquisition slew. The control computer for the pointing system is situated on the gondola. It should be a digital device with the ability to readily change control law parameters when the payload is changed between flights. Attached to the gondola is an elevation gimbal assembly with a torque motor, tachometer, and resolver. If two-axis control is used, the solar scientific instrument mounts directly to the elevation gimbal. If three-axis control is required, there is a cross-elevation gimbal assembly between the elevation gimbal and the science instrument. Like the elevation gimbal assembly, it has a torque motor, tachometer, and resolver. The cross-elevation gimbal assembly should be removed, if not needed by the payload, to save weight. On the interface structure that the science instrument mounts to, there are three single-axis rate gyros for measuring instrument pitch, yaw, and roll rates. There is also an inclinometer for measuring instrument roll orientation. The only hardware on the science instrument is a two-axis Sun sensor for pitch and yaw attitude of the instrument with respect to Sun center.

The pointing system has three modes of operation. They are the gimbal command mode, the Sun acquisition slew mode, and the Sun point mode. Once the balloon is at float altitude and the payload launch clamp has been opened to release the science instrument, the gimbal command mode is enabled, and the science instrument is commanded to a predetermined elevation angle that should be close to the elevation angle of the Sun at the time. If the cross-elevation gimbal assembly is employed, zero cross-elevation gimbal is commanded. The control system block diagrams for the gimbal command mode are shown in figure 1. The second order transfer functions in the forward loops are shaping filters whose coefficients can be uniquely specified for each payload, if necessary, to ensure system stability. Once the science instrument reaches the commanded elevation angle, the Sun acquisition slew mode is also enabled. This slews the gondola and science instrument toward the Sun in azimuth. A block diagram for this mode is shown in figure 2. Once the Sun is in the field-of-view of the instrument-mounted Sun sensor, the Sun point mode is enabled and the other modes are disabled by the control computer. The science instrument is now controlled to point at the Sun. The control system for the Sun point mode has two parts. One part is the control law shown in figure 3. It generates angular acceleration commands in science instrument axes. These are input into the second part, which is the steering law that generates the torque commands for the control actuators. A different steering law is used depending on whether three-axis or two-axis control is employed, as shown in figure 4. In figure 3, the option exists of updating the roll attitude using the inclinometer output in an attitude observer loop. This also compensates for roll rate gyro drift. The ground should have the ability to enable or disable this update loop as it sees fit. Likewise, it should have the ability to uplink the biases $\theta_{P(B)}$ and $\theta_{Y(B)}$ that correct for misalignments between the science instrument line-of-sight and the Sun sensor, determined in flight. Furthermore, the ground should have the ability to uplink the pitch, yaw, and roll offset pointing commands $\theta_{P(C)}$, $\theta_{Y(C)}$, and $\theta_{R(C)}$, respectively.

Finally, the reaction wheel speed control system shown in figure 5 is the last part of the pointing system. It is used in the Sun acquisition slew mode and the Sun point mode to keep the reaction wheel speed from saturating.

III. SIMULATION RESULTS

A computer simulation of the pointing system described in section II was developed by modifying the one in reference 3. The solar scientific instrument was assumed to be the SOUP. It and the gondola were modeled as rigid bodies whose mass characteristics are shown in table 1. The flight train is modeled as a massless and extensionless cable with some torsional stiffness. The balloon can rotate in azimuth and its motion is assumed to be unaffected by the dynamics of the gondola and the science instrument. Other conditions for the simulation are listed in table 1. Four Sun point mode cases were simulated, two with three-axis control and two with two-axis control. For each control configuration, Sun elevation angles of 10 degrees and 80 degrees were simulated. The simulation results are shown in figures 6 to 13. They show good pointing system performance in all cases.

IV. CONCLUSIONS

In summary, this paper has presented a general-purpose balloon-borne pointing system for precise pointing, low cost, and quick launch. It is designed to accommodate a wide variety of solar scientific instruments. It has the option of three-axis control, pitch-yaw-roll, or two-axis control, pitch-yaw, depending on the needs of the payload. Simulation results for both configurations were presented with the SOUP as the scientific instrument. The results indicate good pointing performance for Sun elevation angles ranging from 10 degrees to 80 degrees.

Table 1. Simulation conditions.

I. Mass characteristics:
   A. Science instrument:
      1. Weight = 410 lb
      2. Principal moments of inertia = 6,70,70 s-ft^2
   B. Gondola:
      1. Weight = 2,055 lb
      2. Principal moments of inertia = 635,1392,1439 s-ft^2

II. Maximum control torques = 20 ft-lb in each axis

III. Control bandwidths = 1 hz

IV. Roll attitude observer bandwidth = 0.03 hz

V. Input disturbances:
   A. $\pm$0.25 degrees pendulous oscillations with period = 17 s
   B. Sinusoidal balloon rotations in AZ with peak rates = $\pm$0.42 degrees/s and period = 100 s

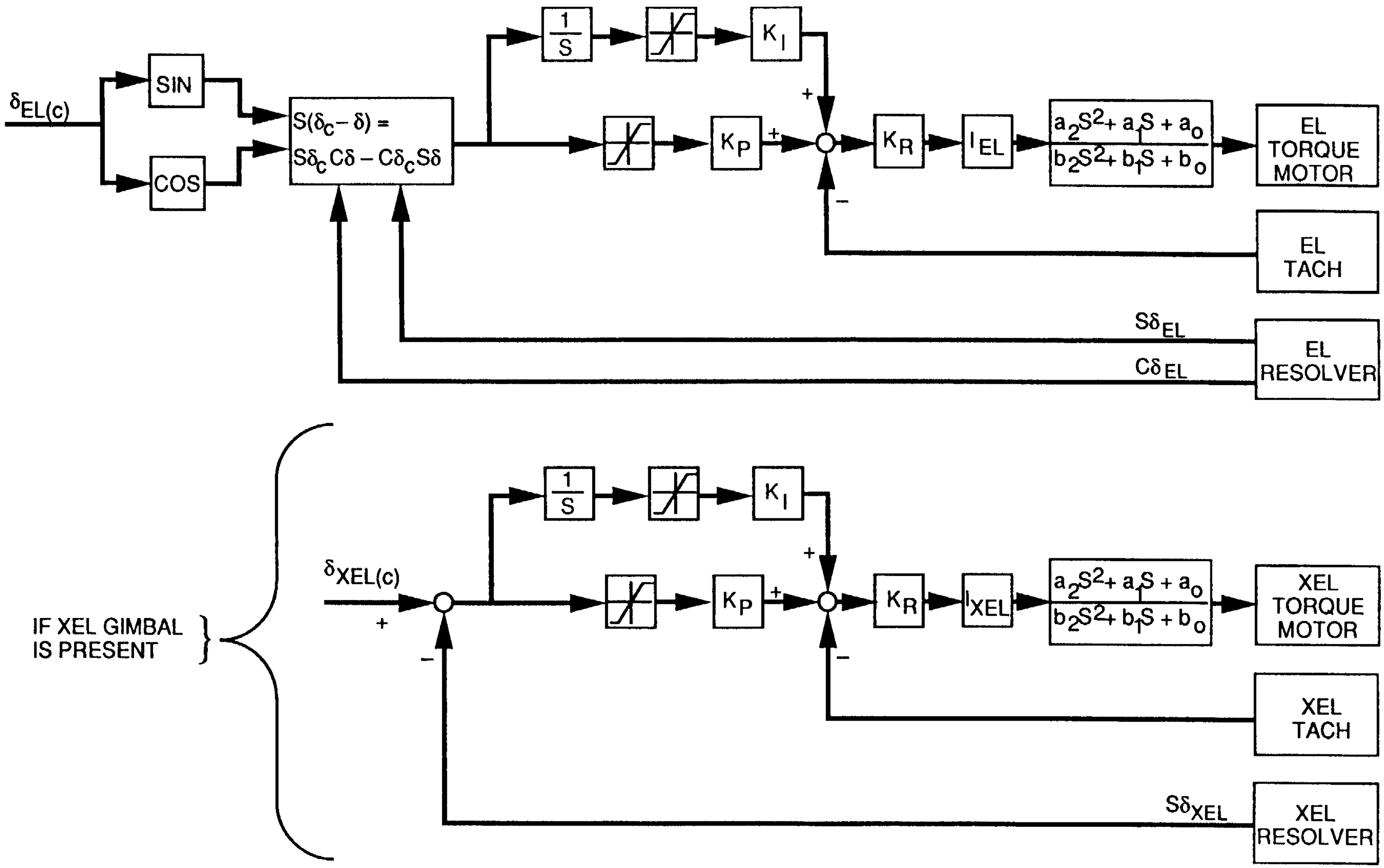

Figure 1. Control system block diagrams for the gimbal command mode.

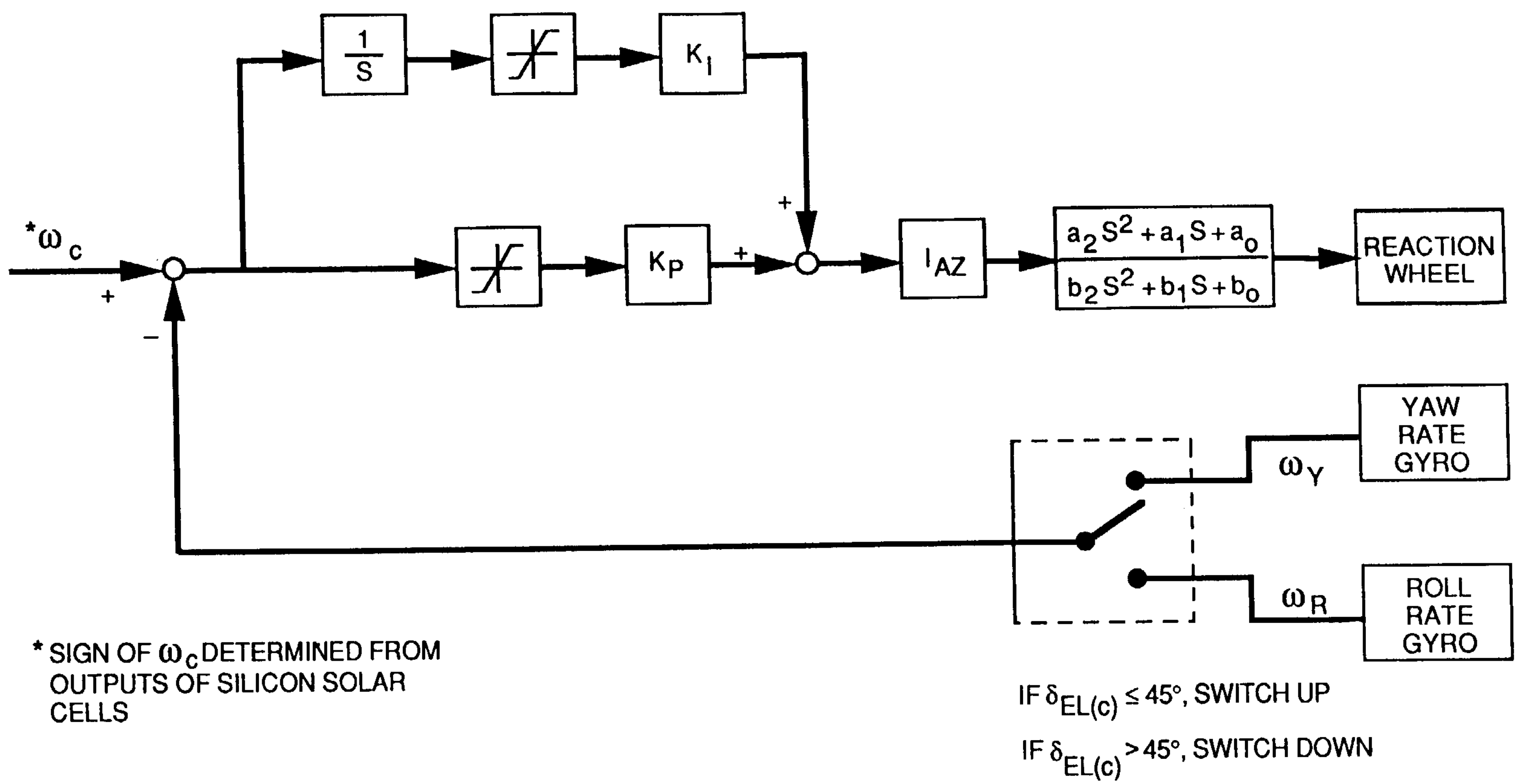

Figure 2. Control system block diagram for the Sun acquisition slew mode.

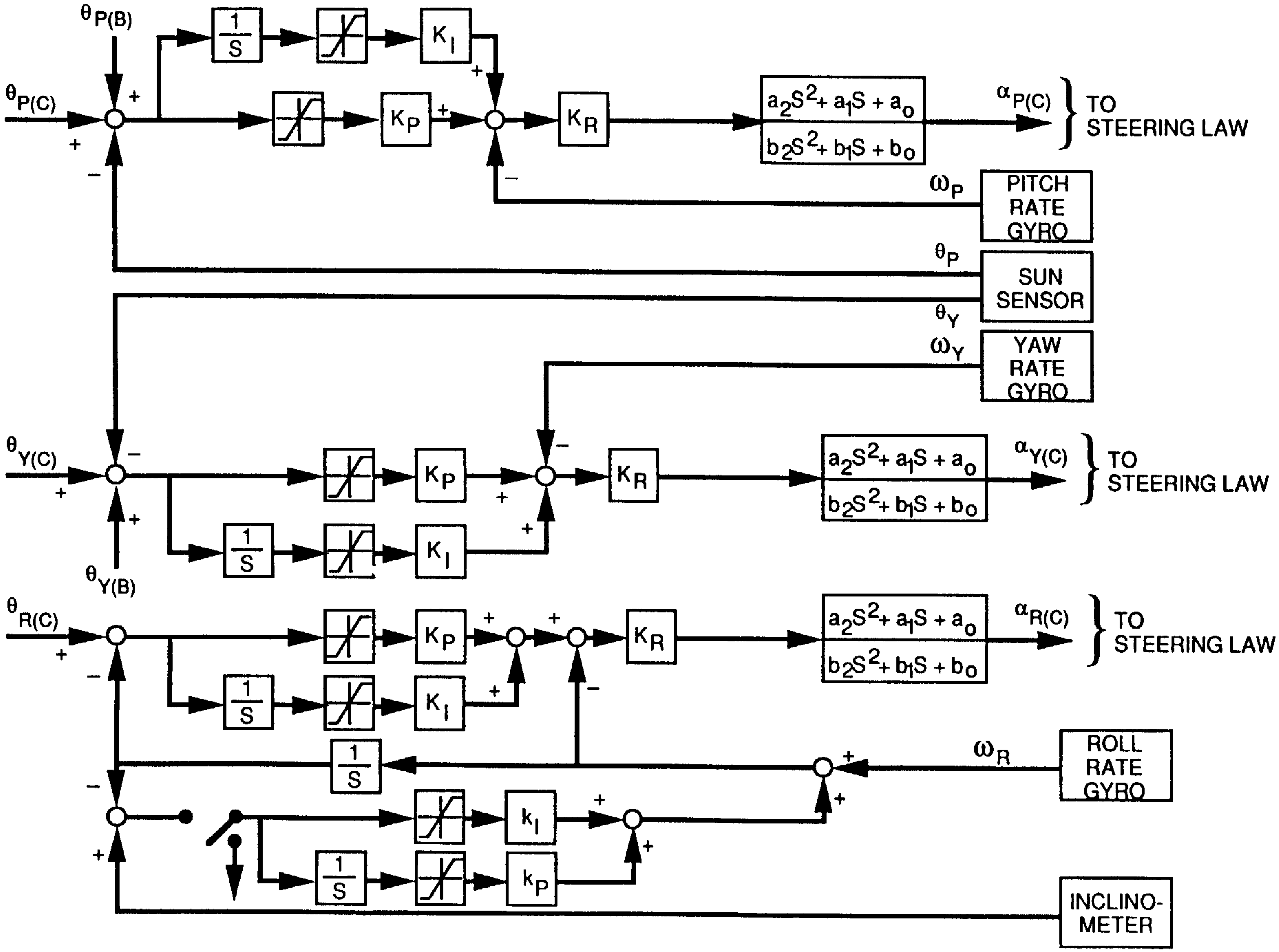

Figure 3. Control law for the Sun point mode.

- FOR PITCH-YAW-ROLL CONTROL (i.e., WITH CROSS-ELEVATION GIMBAL):

$$\begin{Bmatrix} T_{AZ\ RW(C)} \\ T_{EL\ TM(C)} \\ T_{XEL\ TM(C)} \end{Bmatrix} = \begin{bmatrix} \left(\frac{1}{S\delta_{EL}} I_{AZ}\right) & 0 & 0 \\ 0 & I_{EL} & 0 \\ \left(-\frac{C\delta_{EL}}{S\delta_{EL}} I_{XEL}\right) & 0 & I_{XEL} \end{bmatrix} \begin{Bmatrix} \alpha_{R(C)} \\ \alpha_{P(C)} \\ \alpha_{Y(C)} \end{Bmatrix}$$

- FOR PITCH-YAW CONTROL (i.e., WITHOUT CROSS-ELEVATION GIMBAL):

$$\begin{Bmatrix} T_{AZ\ RW(C)} \\ T_{EL\ TM(C)} \\ T_{XEL\ TM(C)} \end{Bmatrix} = \begin{bmatrix} 0 & 0 & \left(\frac{1}{C\delta_{EL}} I_{AZ}\right) \\ 0 & I_{EL} & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} \alpha_{R(C)} \\ \alpha_{P(C)} \\ \alpha_{Y(C)} \end{Bmatrix}$$

NOTE: $S\delta_{EL}$ AND $C\delta_{EL}$ ARE ELEVATION RESOLVER OUTPUTS

Figure 4. Torque command steering laws for the Sun point mode.

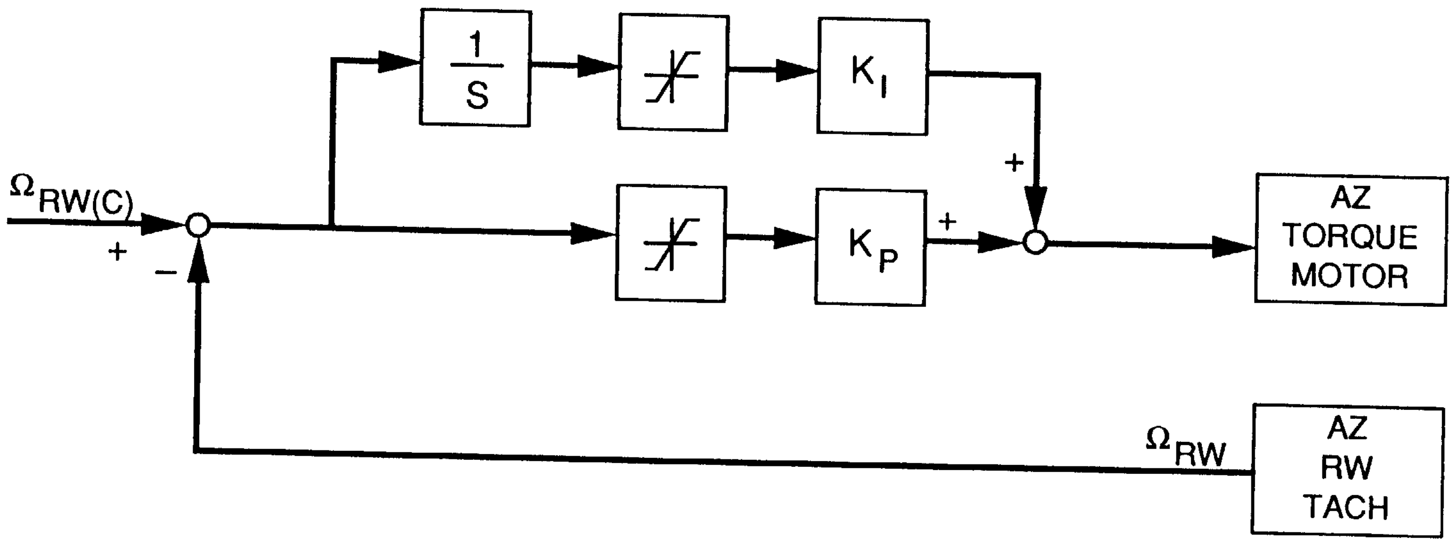

Figure 5. Block diagram for the reaction wheel speed control system.

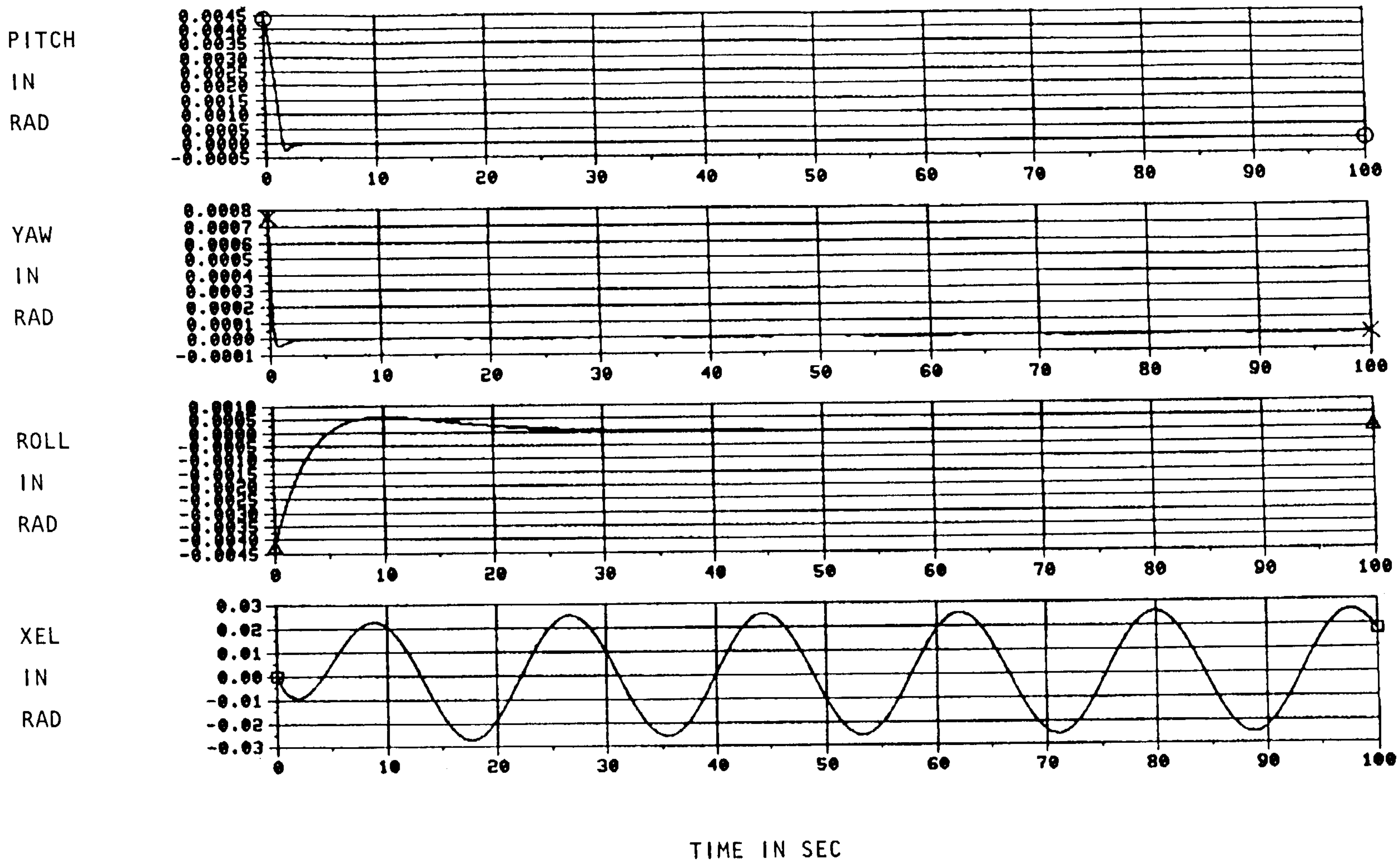

Figure 6. Instrument attitude for three-axis control at 10-degrees Sun elevation angle.

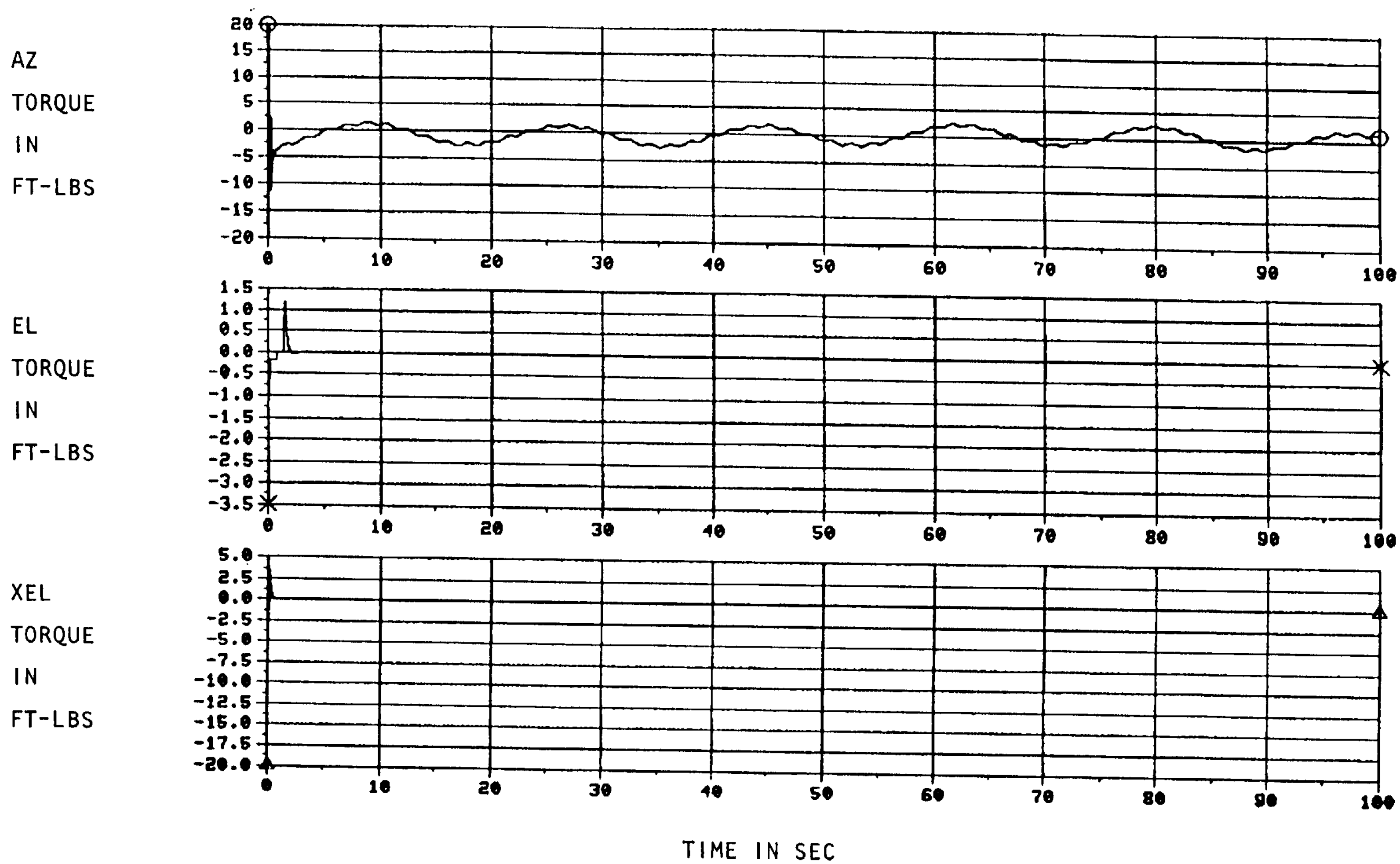

Figure 7. Control torques for three-axis control at 10-degrees Sun elevation angle.

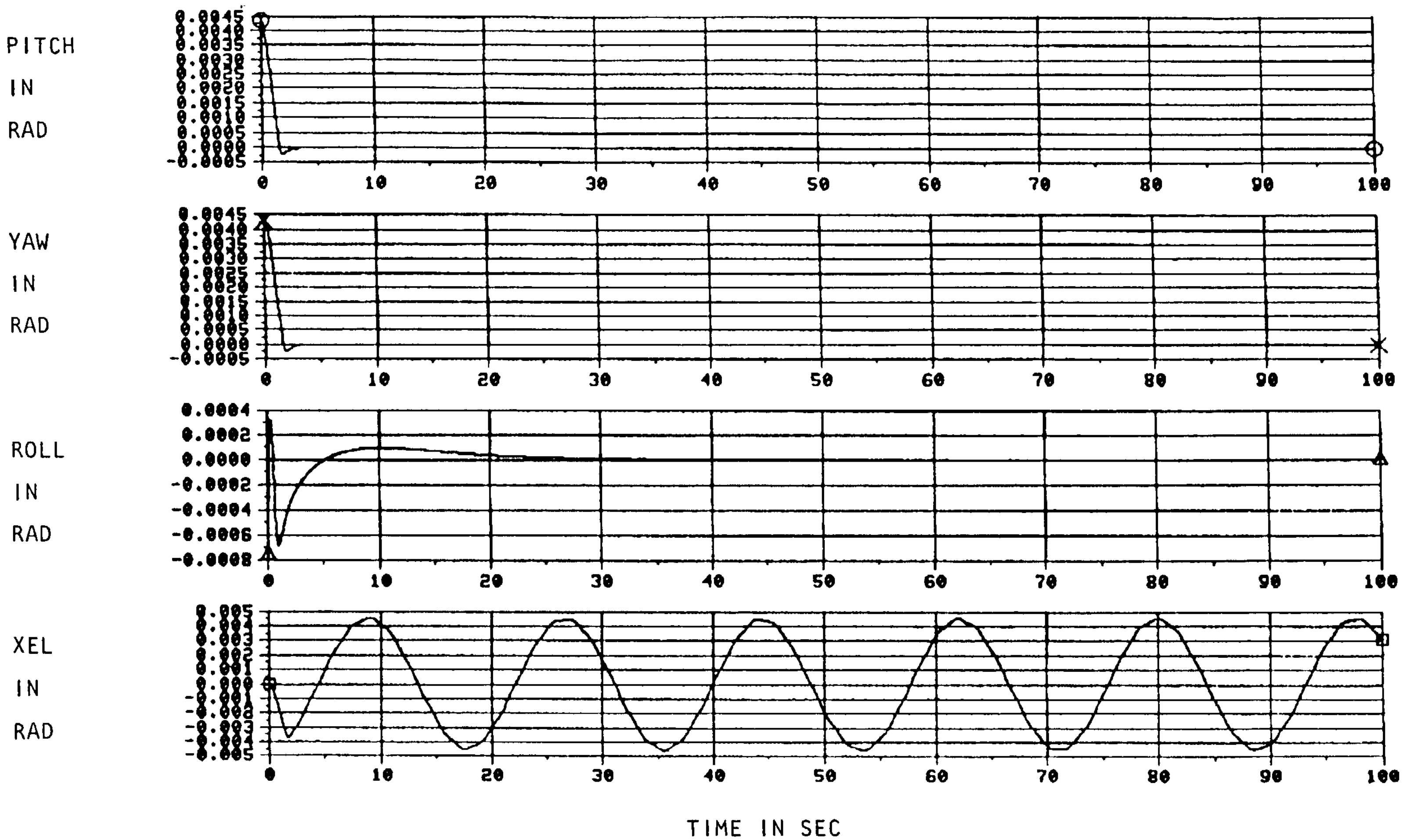

Figure 8. Instrument attitude for three-axis control at 80-degrees Sun elevation angle.

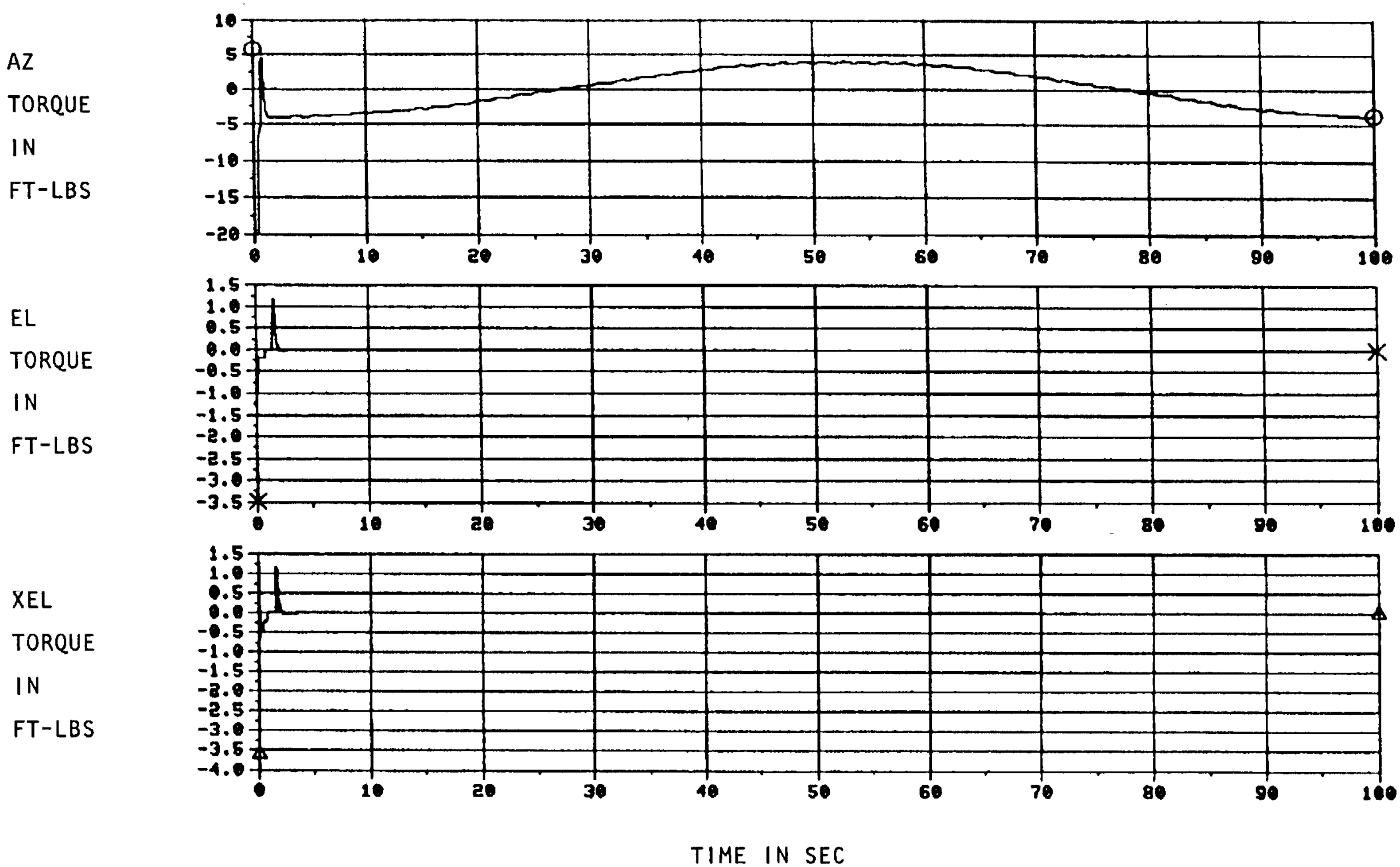

Figure 9. Control torques for three-axis control at 80-degrees Sun elevation angle.

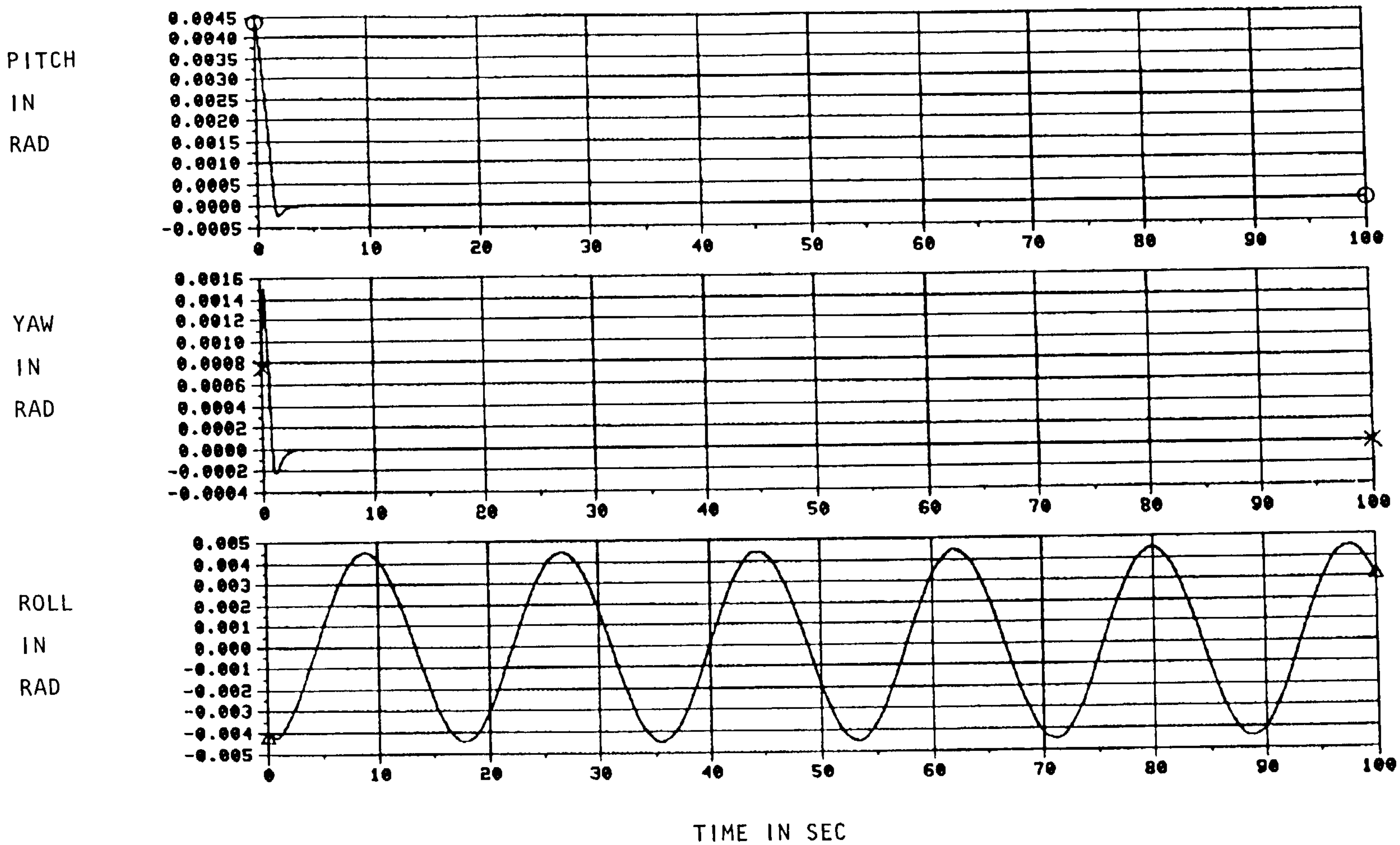

Figure 10. Instrument attitude for two-axis control at 10-degrees Sun elevation angle.

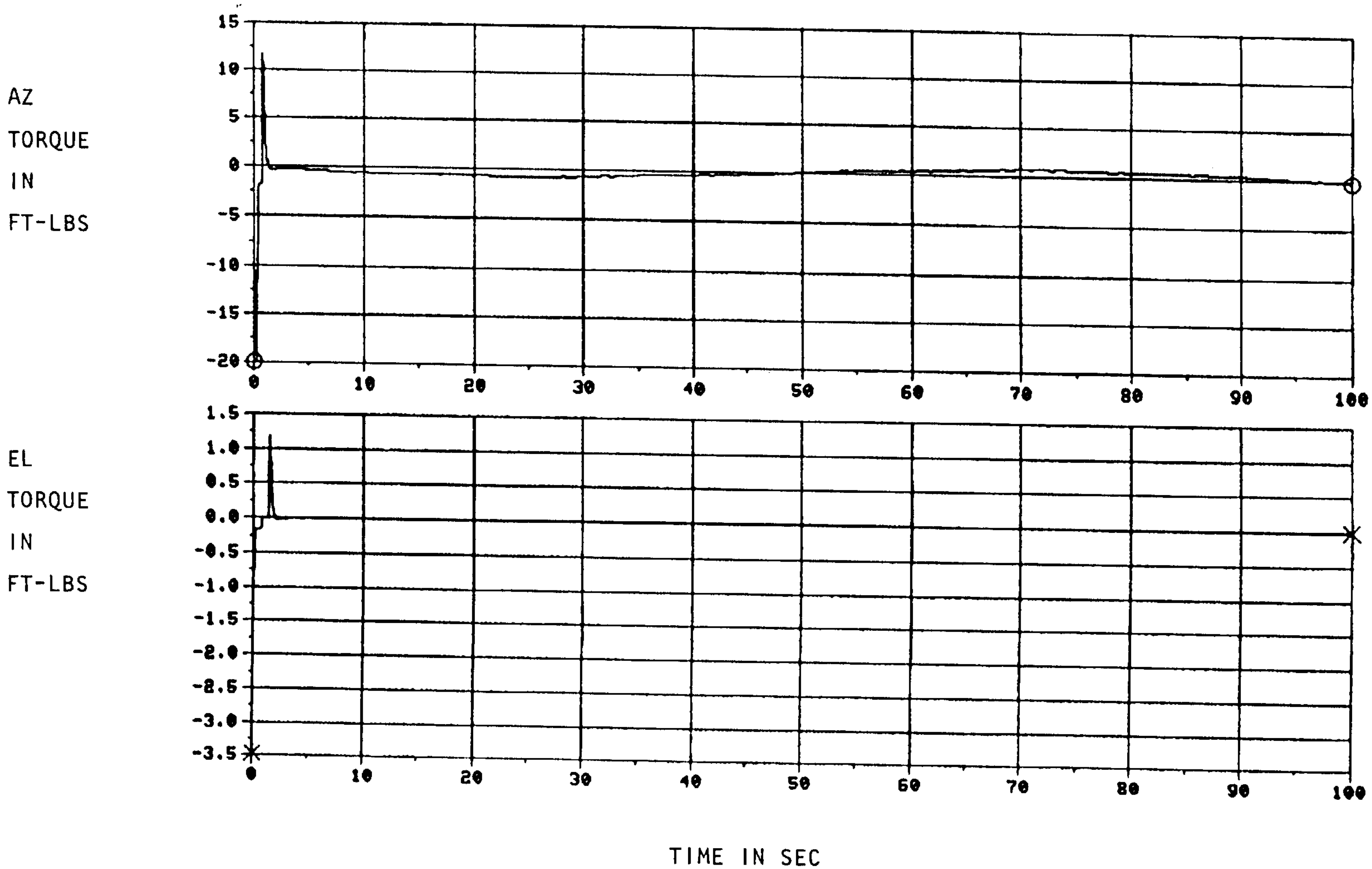

Figure 11. Control torques for two-axis control at 10-degrees Sun elevation angle.

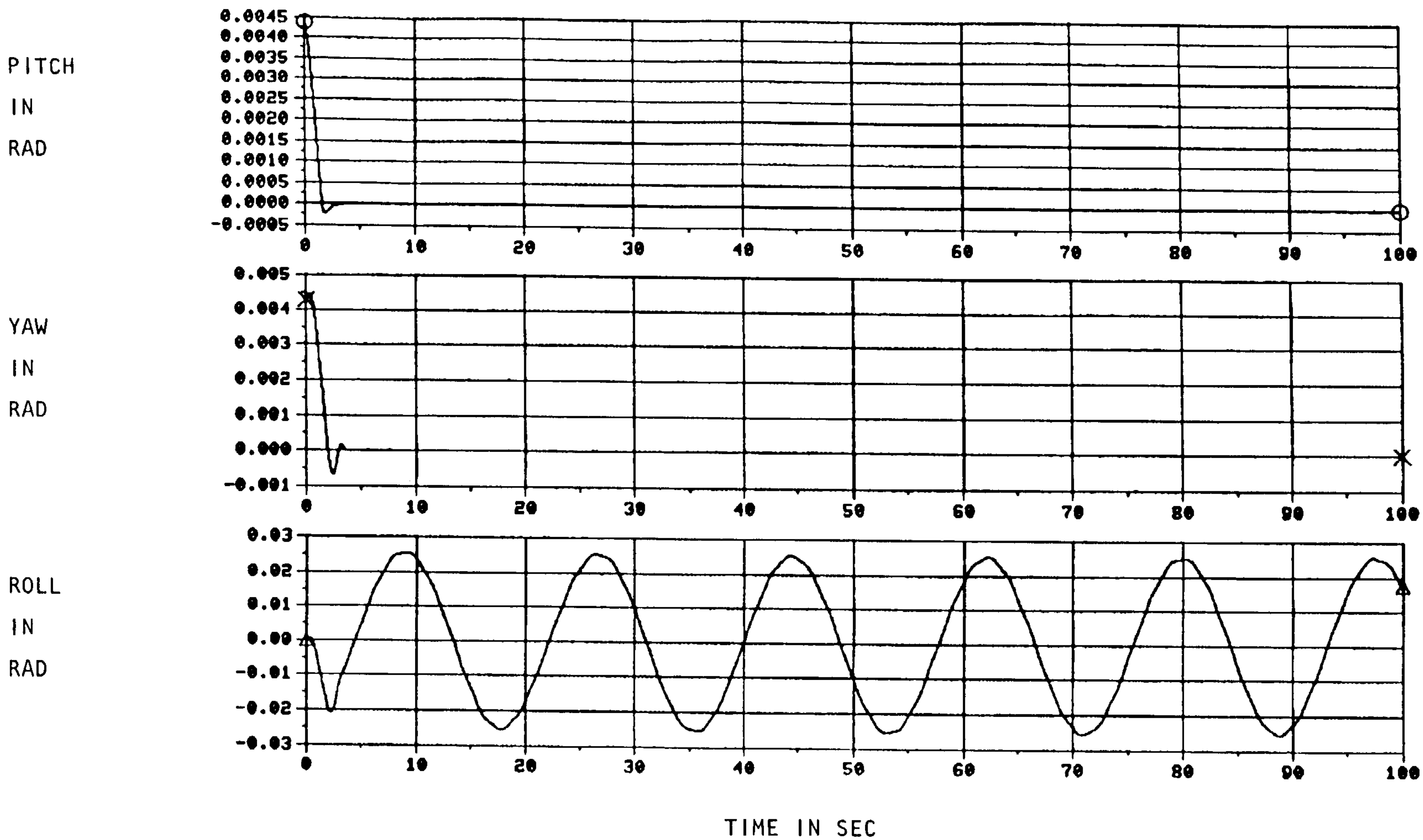

Figure 12. Instrument attitude for two-axis control at 80-degrees Sun elevation angle.

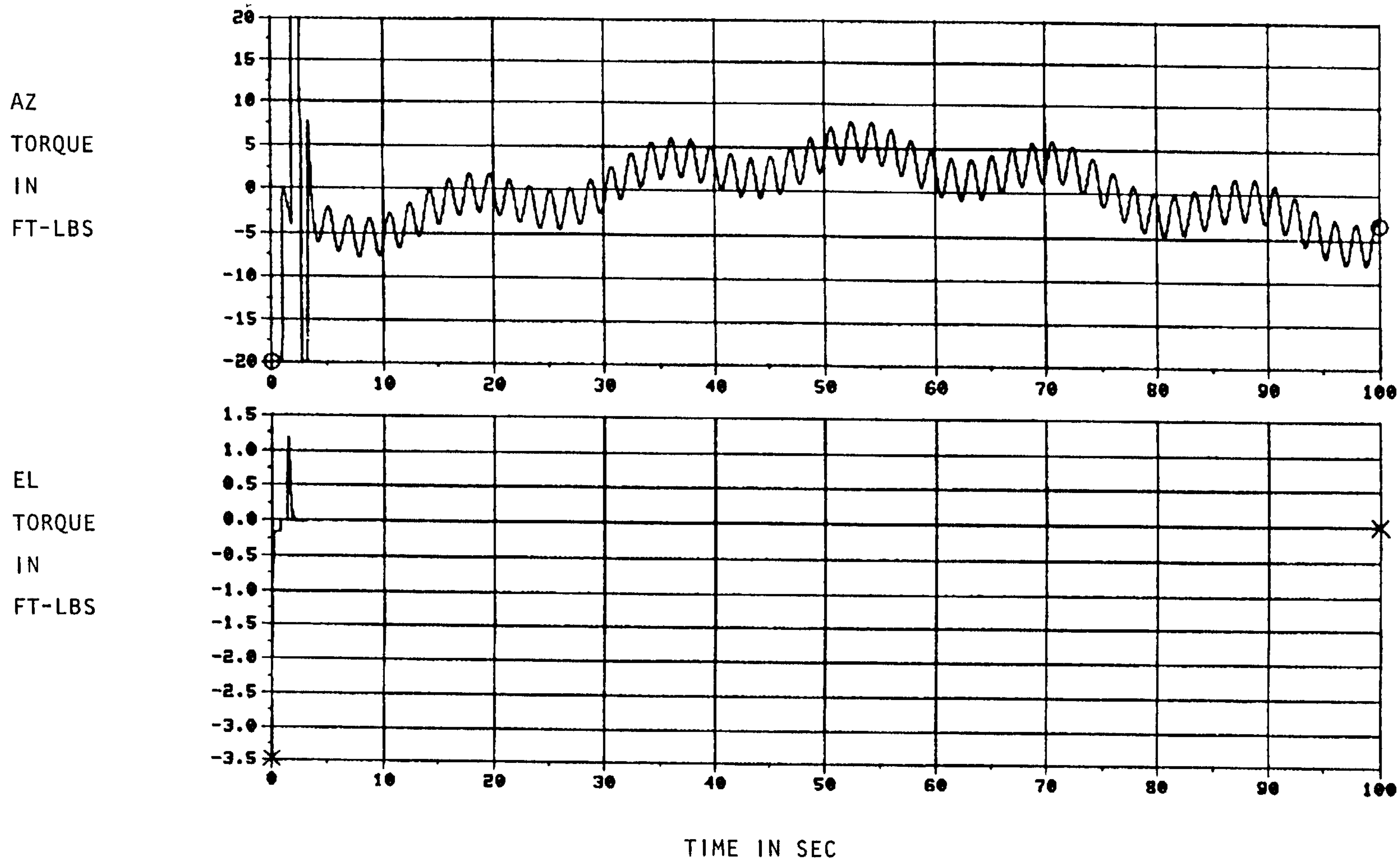

Figure 13. Control torques for two-axis control at 80-degrees Sun elevation angle.

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16. Abstract

This paper describes a general-purpose balloon-borne pointing system for accommodating a wide variety of solar scientific instruments. It is designed for precise pointing, low cost, and quick launch. It offers the option of three-axis control, pitch-yaw-roll, or two-axis control, pitch-yaw, depending on the needs of the solar instrument. Simulation results are presented that indicate good pointing capability at Sun elevation angles ranging from 10 degrees to 80 degrees.

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