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A TWO-AXIS LASER BORESIGHT SYSTEM FOR A SHUTTLE EXPERIMENT

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ABSTRACT

A two-axis gimballed laser pointing mechanism is being developed for the Lidar In-space Technology Experiment (LITE) to be flown on the National Space Transporation System (NSTS) Space Shuttle in February 1993. This paper will describe the design requirements and goals, the configuration, analysis, and testing plans for this highly stable, high-resolution, high-energy laser pointing device.

INTRODUCTION AND BACKGROUND

There are two main objectives of LITE, the first being to evaluate a light detection and ranging (LIDAR) system's operation in space. The second objective is to obtain measurements of planetary boundary layer and cloud top heights, tropospheric and stratospheric aerosols, and atmospheric temperature and density using the LIDAR technique. LITE (see Fig. 1) consists of an Nd:YAG Laser Transmitter Module emitting a 10-Hz pulsed beam at three wavelengths (1064 nm, 532 nm, and 355 nm), a Telescope-Receiver, Instrument Electronics, and a Boresight System. All LITE components are mounted on an aluminum orthogrid platform structure that is carried on a standard Spacelab 3-m pallet.

As the transmitted laser pulses propagate through the atmosphere, a portion of the beam will be directly backscattered and collected by the Telescope-Receiver. The Telescope-Receiver consists of a 1-m telescope and an aft optics assembly containing the necessary lenses, filters, and detectors needed to measure the intensity of the backscattered pulses. The Boresight System turns the transmitted beam 90 deg toward Earth and maintains its colinearity with the Telescope-Receiver. The Boresight System (see Fig. 2) is a closed-loop control system that utilizes a quadrant photomultiplier detector located in the aft optics to monitor the position of the return beam. If the returning beam pulses are not colinear with the telescope axis, the quadrant detector generates positional error signals to the Boresight Electronics. The Electronics then command the Boresight Assembly to redirect the outgoing beam pulses to null the error signals and thus align the experiment. Figure 3 shows a computer-generated model of this Boresight Assembly, which is a two-axis laser pointing mechanism and is the subject of this paper.

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DESIGN REQUIREMENTS AND GOALS

The Boresight System is required to maintain colinearity between the transmitted laser beam and the Telescope-Receiver axis to within 50 microradians. This is accomplished through a closed-loop system that steers the outgoing beam. The system must be able to search for and lock in on a return signal anywhere within the telescope field of view. The system is activated only when it is desired to check or adjust the boresight and does not continuously adjust boresight setting during lidar operations; therefore, the system is required to maintain alignment in a passive, unpowered mode. The mechanism must have a dynamic adjustment range of ±1.0 deg and must be able to efficiently redirect all three wavelengths of the Laser Transmitter Module 90 deg toward Earth. The mechanism must also have the capability of being driven back to its initial on-orbit position at any time during the mission.

Some additional design goals exist for the Boresight Assembly. One goal is a first mode vibrational natural frequency above 35 Hz to avoid the main launch excitation frequencies. The minimizing of thermal distortions that could affect pointing accuracy and stability and the protection of the reflecting surface from contamination are two other design goals.

CONFIGURATION DESCRIPTION

A cross-sectional layout of the Boresight Assembly is shown in Figure 4. It utilizes a stepping motor and harmonic drive gear reduction to produce a 1.543 arcsec per step angular positioning resolution in each axis. This translates to a 14.96 microradian pointing resolution of the beam, well within the 50 microradian requirement. The unit is constrained using mechanical limit stops to a maximum travel of ±0.5 deg in each axis, which, due to the 90-deg deflection, translates to the required ±1.0-deg dynamic adjustment range of the outgoing beam. The two motors are space-flight qualified samarium-cobalt permanent magnet, brushless, stepping motors with integrally-mounted, high-capacity, spur gearheads that rotate 0.0857 deg/step. Each motor is connected to a harmonic drive gear reducer via a zero backlash flexible coupling, the design of which will be described later.

The harmonic drive consists of an elliptical wave generator inside an externally-toothed flexspline which is, in turn, mounted inside an internally-toothed circular spline with two more teeth than the flexspline. Figure 5 illustrates the operating principle of the harmonic drive. For every full rotation of the wave generator (driven by the stepping motor), the flexspline rotates by two teeth. Thus, for the 400-toothed flexspline used in this application, a 200:1 gear reduction is achieved. This converts the 0.0857 deg/step rotation of the stepping motor to a resulting 0.000429 deg/step or 1.54 arcsec/step output. Also, a preload is created by the elliptical wave generator which results in a purely radial engagement of the teeth of the flexspline and circular spline. This allows the harmonic drive to operate with essentially zero backlash. Reference 1 gives a much more detailed description of the functioning of the harmonic drive.

Flexural pivots are used in each axis instead of bearings due to the high rotational stiffness and small total angular travel required. The two 1-inch diameter cantilever-type flexural pivots need no lubrication; therefore, they are ideally suited to a space environment where bearing lubrication is often a problem. Each pivot acts as a torsional spring with a spring rate of 0.0864 kg-m/deg (120 in.-oz/deg). This requires 0.0432 kg-m (60 in.-oz) of motor torque to drive each pivot to its maximum desired deflection of 0.5 deg. Each stepping motor has a driving torque of 0.0173 kg-m (24 in.-oz) and an unpowered detent torque (due to the permanent magnet) of 0.0504 kg-m (70 in.-oz), which, with the 200:1 gear reduction of the harmonic drive, become 3.456 kg-m (4800 in.-oz) and 10.081 kg-m (14000 in.-oz) respectively. Thus, at the 0.5 deg maximum flexpivot displacement, the motor is loaded at 0.0864/3.456 or 1.25 percent of its rated maximum torque and 0.43 percent of its detent torque. The remaining 10.038 kg-m (13940 in.-oz) of detent torque causes the Boresight Assembly to be very rotationally stiff, thereby satisfying the requirement of being able to maintain alignment in a passive, unpowered condition. Reference 2 gives more detail on the functioning of the flexural pivot.

A modular incremental encoder is employed to measure the angular output position of each axis. An encoder is used, rather than a Rotary Variable Differential Transformer (RVDT) on the motor shaft or by the counting of motor steps, because it directly measures the actual rotation of the output shaft. It gives positive feedback that the system has responded to a given command and that the reflecting surface has been moved. It also eliminates the possibility of missed motor steps or other errors in shaft coupling between the motor and the actual output causing an incorrect angular position reading. The encoder enables the system to satisfy the requirement of being able to be driven back to its initial on-orbit position. the encoder operates by shining light through a transparent disk with lines scribed radially on it, into a detector. The disk is mounted to the output shaft of the harmonic drive and as it rotates, the lines pass through the light creating a square wave pattern at the detector which is converted by the encoder electronics into an angular position. The angular resolution is limited by the number of lines that can be scribed on the disk and the amount of signal interpolation that can be achieved by the electronics. The Boresight Assembly uses a 4500 line disk and 40x signal interpolation to give a 360 deg/(4500x40) or 0.002 deg resolution of the encoder. This is probably the best resolution that can be hoped for with the existing encoder technology and a four-inch diameter disk envelope.

A 70-mm right angle prism is used as the reflecting surface. It is preferred over a mirror since the total internal reflection of the prism is the most efficient way to transmit all three LITE wavelengths. It can transmit the 0.15 J/pulse at 355 nm, 0.40 J/pulse at 532 nm, and 0.20 J/pulse at 1064 nm emitted by the Laser Transmitter simultaneously, with over 99-percent efficiency. In contrast, a coated aluminum mirror can have an efficiency as low as 87 percent which can lead to localized heating of the mirror due to absorption. This could cause the mirror to warp and also potentially damage the reflective surface. The front and top faces of the prism will be canted by 2 deg to prevent any reflections off the prism faces from going back into the Laser Transmitter and possibly quenching the laser rod.

The Boresight Assembly is enclosed by a housing (see Fig. 6) to protect the prism from contamination. The housing is connected to the Laser Transmitter Module via a bellows which provides a light-tight, contamination-proof seal, yet permits relative motion of the structures during the launch vibration environment. The laser beam pulses leave the housing through an optical window that has a motorized, movable cover to protect it from contamination. The center of the cover will be made of an optical material to allow the experiment to obtain some data in the event of a stuck cover. The housing will be covered with MultiLayer Insulation (MLI) thermal blankets to minimize the temperature variations that could affect pointing accuracy during LIDAR operations. This housing enables the system to achieve the second and third design goals of minimizing thermal distortions and preventing reflective surface contamination.

As mentioned previously, zero backlash flexcoupling is used to connect each motor shaft to each harmonic drive wave generator. The flexcoupling (see Fig. 8) is a hollow tube within a hollow tube that acts like an axially stiff bellows in that it will allow a small degree of shaft misalignment and radial runout, yet transmits torque with zero windup or backlash and axially locates the wave generator within the flexspline. This flexcoupling combines with the zero backlash harmonic drive and very low backlash stepping motor to maximize stepping accuracy and repeatability while eliminating any possible hysteresis effects. The flexcoupling is machined entirely from a block of 6061-T6 aluminum, and thus the existing inner tube dimensions are driven by current machining capabilities as well as the required axial and torque loading. The flexcoupling stiffness, expressed by the amount of radial runout allowed, R, and the corresponding load on the motor shaft, F, is a function of the tube geometry and material. There is a linear relationship between F and R, which, for the existing configuration is, $F = R \times 3308$ N/cm. Thus, for an expected 0.000254 cm (0.0001") runout, the shaft load would be 0.840 N (0.189 lb), which is easily withstood by the motor.

ANALYSIS

A Finite Element Model (FEM) has been created (see Fig. 7) and used to determine system vibrational modes and natural frequencies, as well as stress loading and displacements during shuttle launch and landing load conditions. The vibration results (see Table 1) indicate a first mode natural frequency at 45.7 Hz and is a rocking motion of the upper housing on the lower output shaft. This satisfies the remaining design goal of having a first mode natural frequency greater than 35 Hz. The highest stresses (984.2 kg/cm^2 (14000 psi) occur in the lower output shaft and are well below the 2320 kg/cm^2 (33000 psi) cutoff for a positive margin of safety for the 7075-T73 aluminum shaft material. A detailed stress analysis of the Boresight Assembly has been conducted to confirm these results.

TESTING PLANS

The Boresight Assembly has been fabricated and is being assembled. Upon completion, the system will undergo tests to determine and verify the predicted resolution, accuracy, response time, and search and reset routines. The motor for the housing output window cover will also be functionally tested to verify its performance. A vibrational survey will then be conducted to verify the FEM predicted modes. A rotational stiffness test will be performed to verify the system's ability to passively maintain alignment. A thermal/vacuum test will be run to verify the system's ability to withstand the space environment. Following these tests, the unit will be integrated into the LITE instrument and undergo full-up instrument testing.

CONCLUSION

At this stage in the development of the LITE Boresight Assembly, it appears that all of the existing design requirements will be met and proposed design goals will be achieved. System testing will be utilized in combination with past, present, and future analyses to fully prove the design.

There are many possible future applications for this highly stable, high-resolution, high-energy laser pointing system including a possible follow-on to LITE called the Tropical Atmospheric Lidar Observing System (TALOS), an instrument that is proposed to be permanently mounted on the Space Station Freedom.

REFERENCES

1. Carlson, J. H.: Harmonic Drives for Servomechanisms. Machine Design, Penton/IPC, Inc., Cleveland, OH, January 10, 1985.

2. Seelig, F. A.: Effectively Using Flexural Pivots. ASME Publications, United Engineering Center, New York, NY, February, 1970.

Table 1. FEM predicted natural frequencies (lowest 4)

Mode	Frequency	Mode Shape
1	45.7 Hz	Torsion of lower shaft
2	66.6 Hz	Vertical motion of lower shaft
3	93.1 Hz	Vertical motion of upper shaft
4	113.3 Hz	Front-back motion of upper shaft

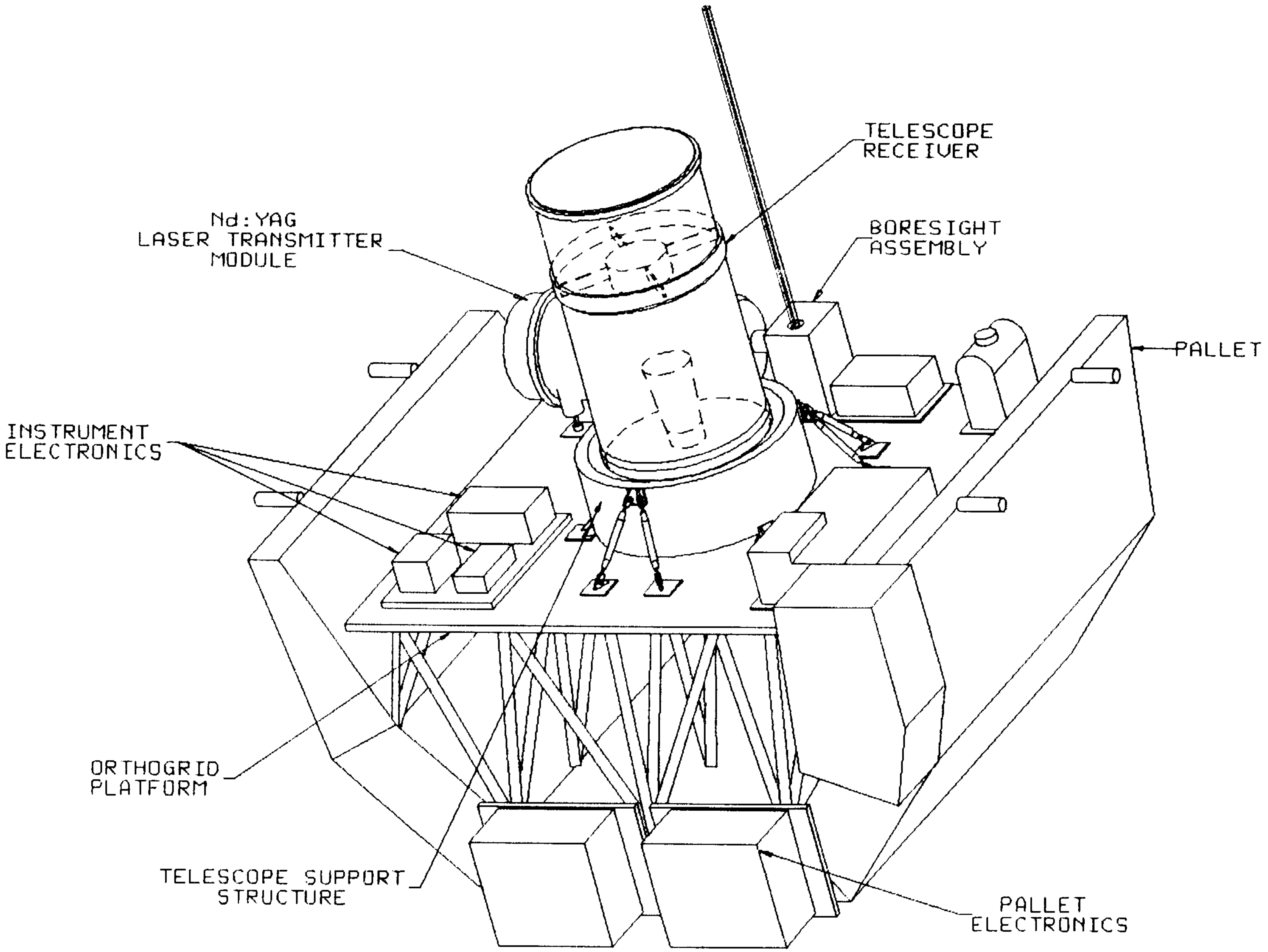

Figure 1. Lidar In-space Technology Experiment (LITE).

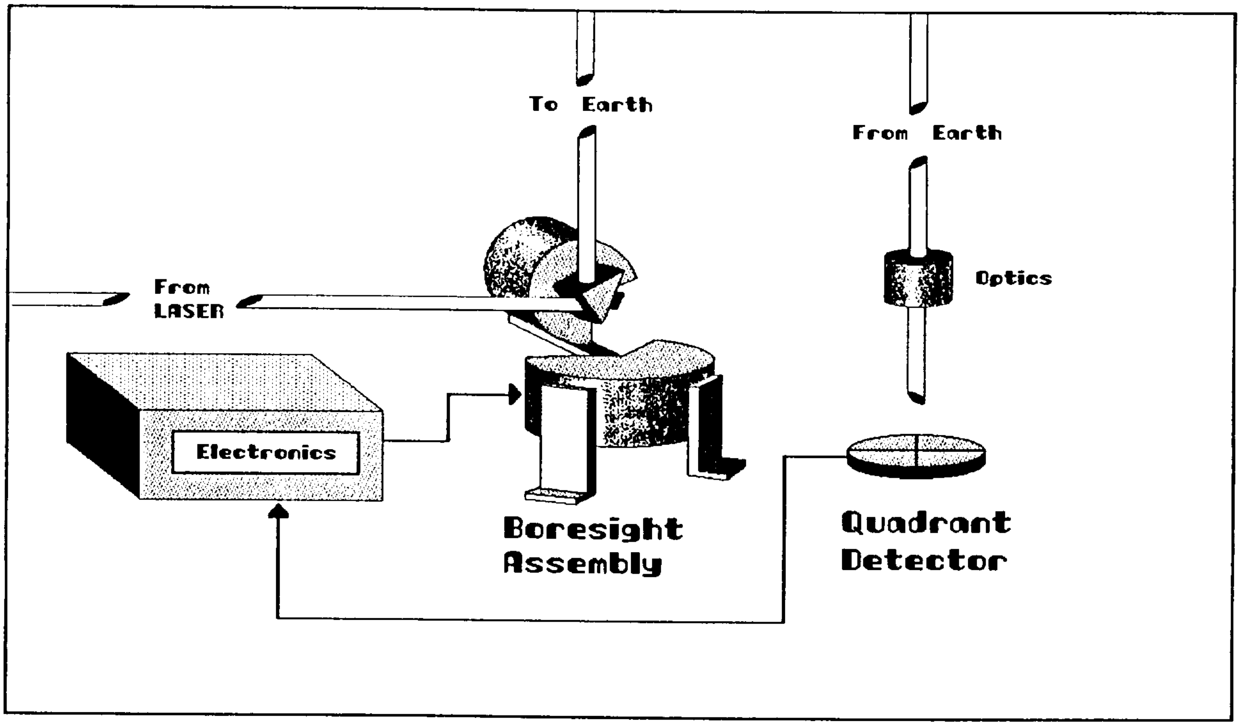

Figure 2. LITE boresight system.

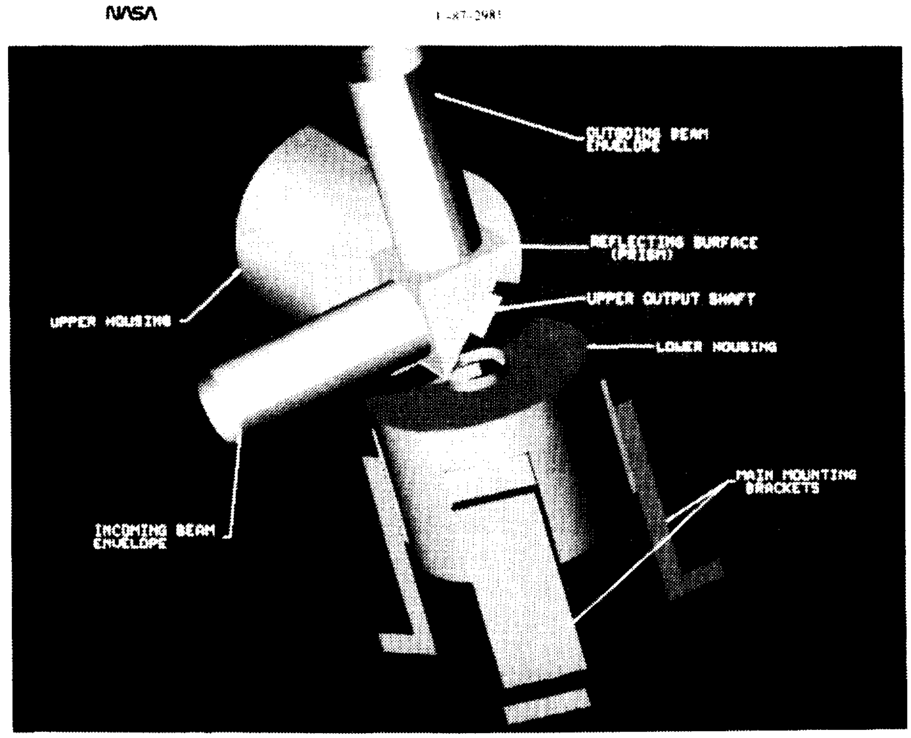

Figure 3. LITE boresight assembly model.

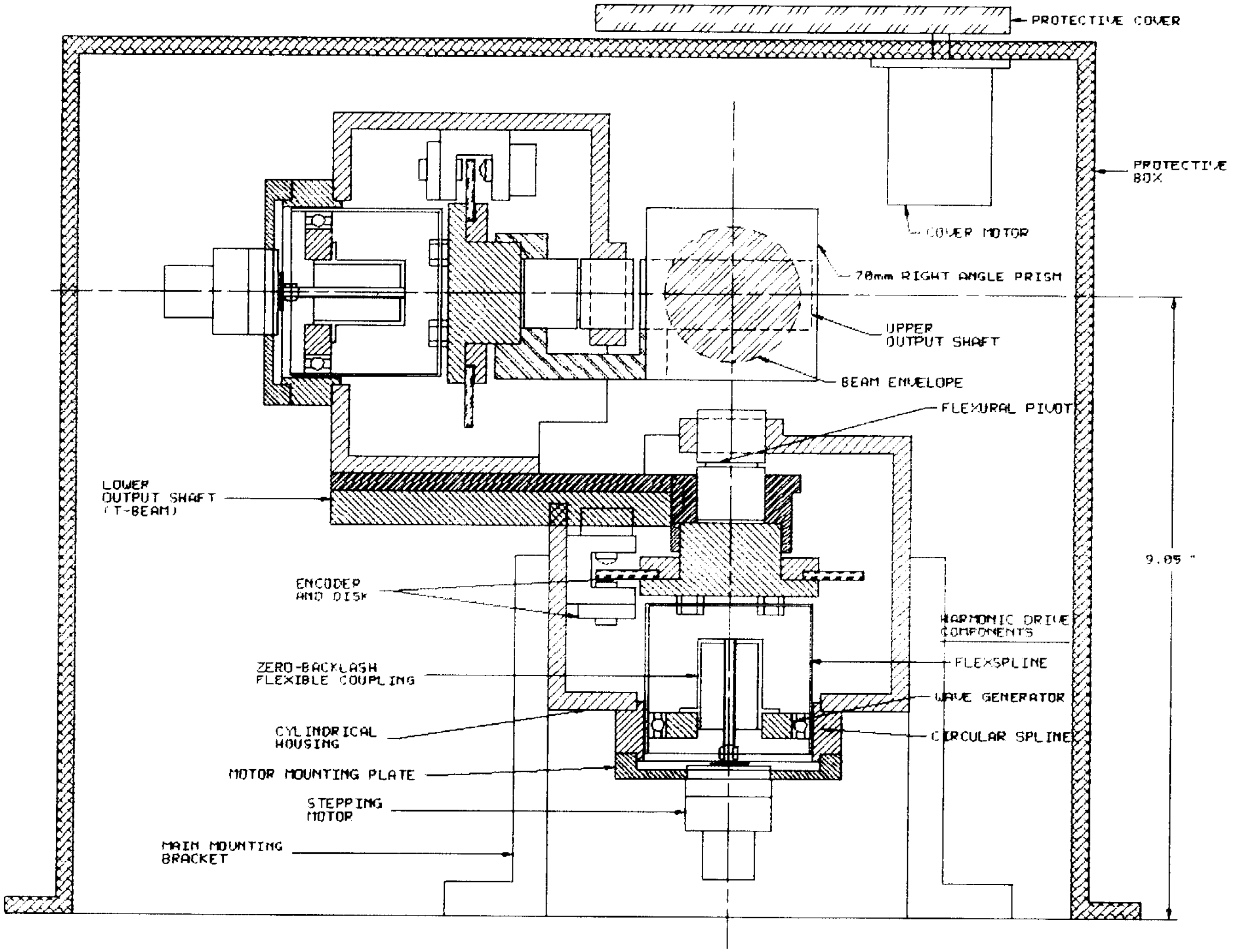

Figure 4. LITE boresight assembly cross-sectional layout.

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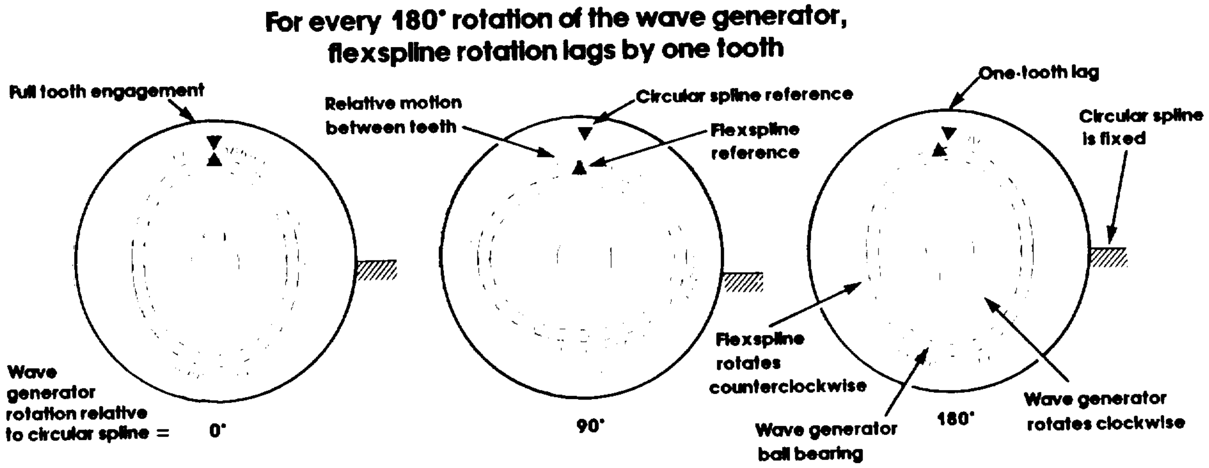

Figure 5. Harmonic drive operating principle.

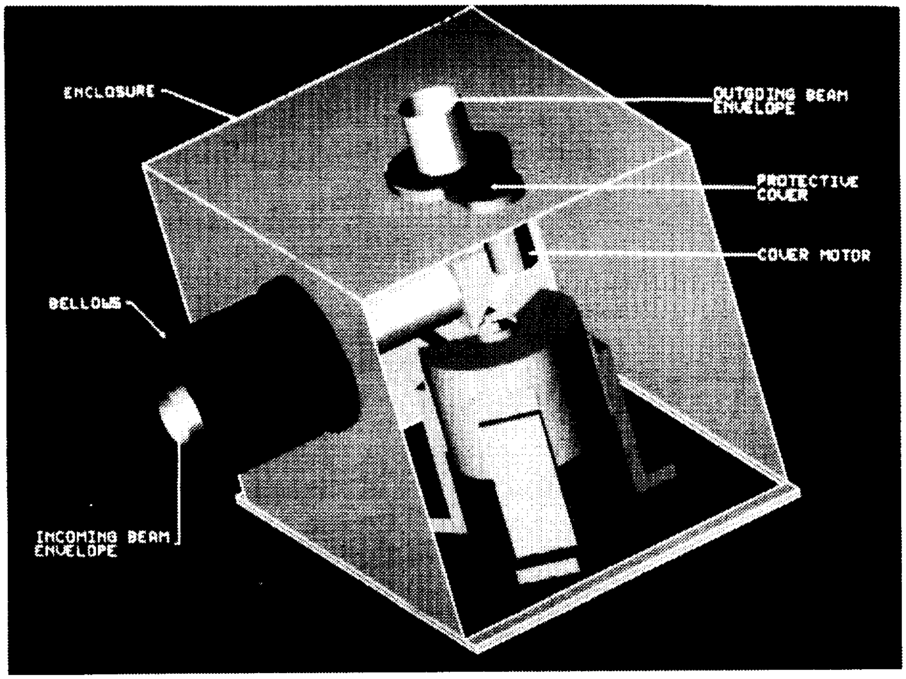

Figure 6. LITE boresight housing model.

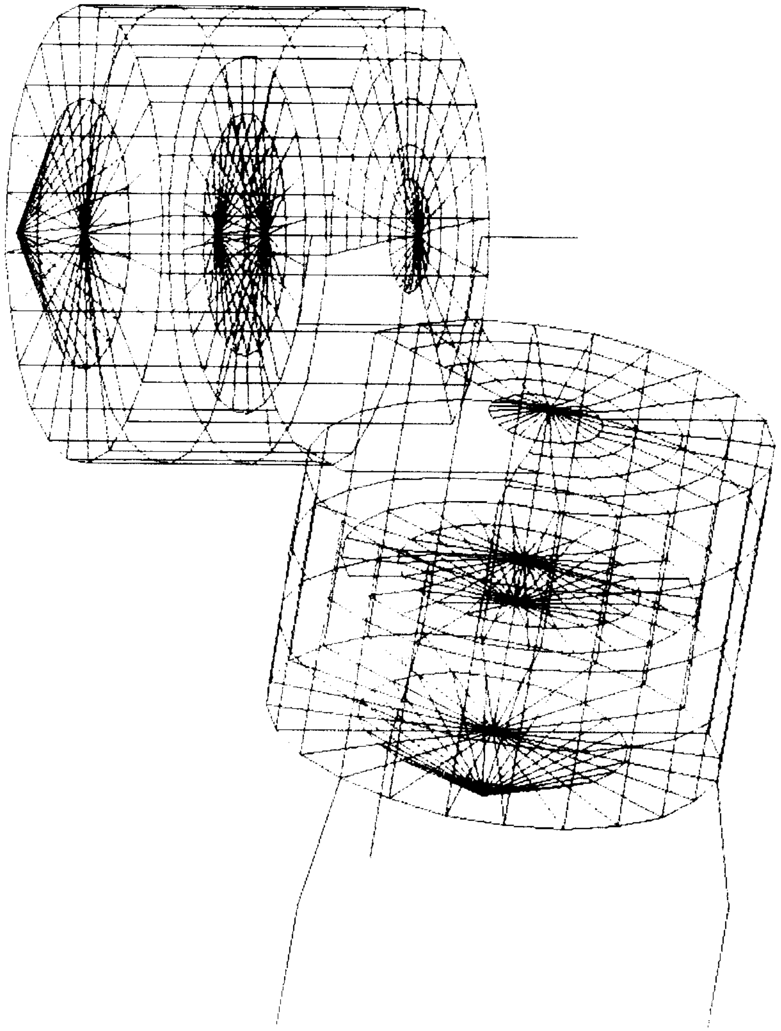

Figure 7. LITE boresight assembly finite element model.

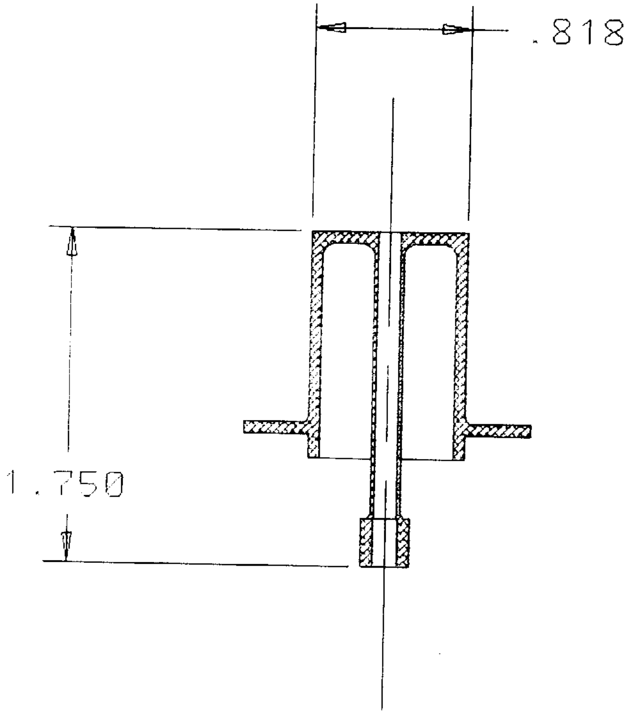

Figure 8. Flexcoupling cross-section.