SPATIAL, HIGH-ACCURACY, POSITIONING-ENCODING SENSOR (SHAPES) FOR LARGE SPACE SYSTEM CONTROL APPLICATIONS

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INTRODUCTION

The Spatial, High-Accuracy, Position-Encoding Sensor (SHAPES) is a controls sensor suitable for the determination of the static shape and vibrational motion of large space structures and similar systems and for the determination of position and velocity in rendezvous and docking. It uses a combination of electro-optical techniques to measure the three-dimensional coordinates distributed over the structure at reading rates high compared to the rates at which the coordinates are changing. The technical approach is that of measuring the distance to and the direction of points on the structure from a single sensor head. Many points can be measured simultaneously from a single head without significantly increasing the complexity of the system. Figure 1 is a table giving an abbreviated summary of measurement performance requirements for flexible spacecraft control sensors. This table has been compiled from many sources but is generally characteristic of what would be required by large antennas requiring surface accuracies of 1/10 to 1/50 of the operating wavelength. The number of points on the structure which must be sensed for dynamic control is smaller than the entry given in the table for static shape determination by about five times.

<table>
<tr><th></th><th>REQUIRED PRECISION</th><th>RANGE OF VARIABLE</th><th>NUMBER OF MEASURED POINTS</th><th>BANDWIDTH</th></tr>
<tr><td>RANGE</td><td rowspan="2">±0.2 mm
TO
±0.03 mm</td><td rowspan="2">±0.1 m</td><td rowspan="5">50 TO 150
(STATIC
SHAPE)</td><td rowspan="5">0.1 Hz
TO
10 Hz</td></tr>
<tr><td>LATERAL DISTANCE</td></tr>
<tr><td>ANGULAR DISPLACEMENT</td><td rowspan="3">±2 arc sec
TO
±0.1 arc sec</td><td rowspan="3">±3 arc min</td></tr>
<tr><td>ROTATION</td></tr>
<tr><td>TWIST</td></tr>
</table>

Figure 1

SHAPES -

SPATIAL, HIGH-ACCURACY, POSITION-ENCODING SENSOR

The basic components of the system are illustrated in figure 2. A pulsed light source floods the area containing the points to be measured with light. The points are designated by reflectors. The light returned to the sensor head from the reflectors is imaged on a streak tube. The tube can be operated in two modes: (1) a non-swept one which determines the location of the images on the face of the tube and (2) a swept mode which determines the time of arrival of the returned pulses. The first mode is used to determine the directions of the reflector from the sensor head while the second is used to determine their distances. The accuracy of the time-of-flight measurements is greatly increased by providing a fiber reference signal via a fiber-optics link and measuring the differences in the time of arrival of the pulses from the reflector and the reference pulses.

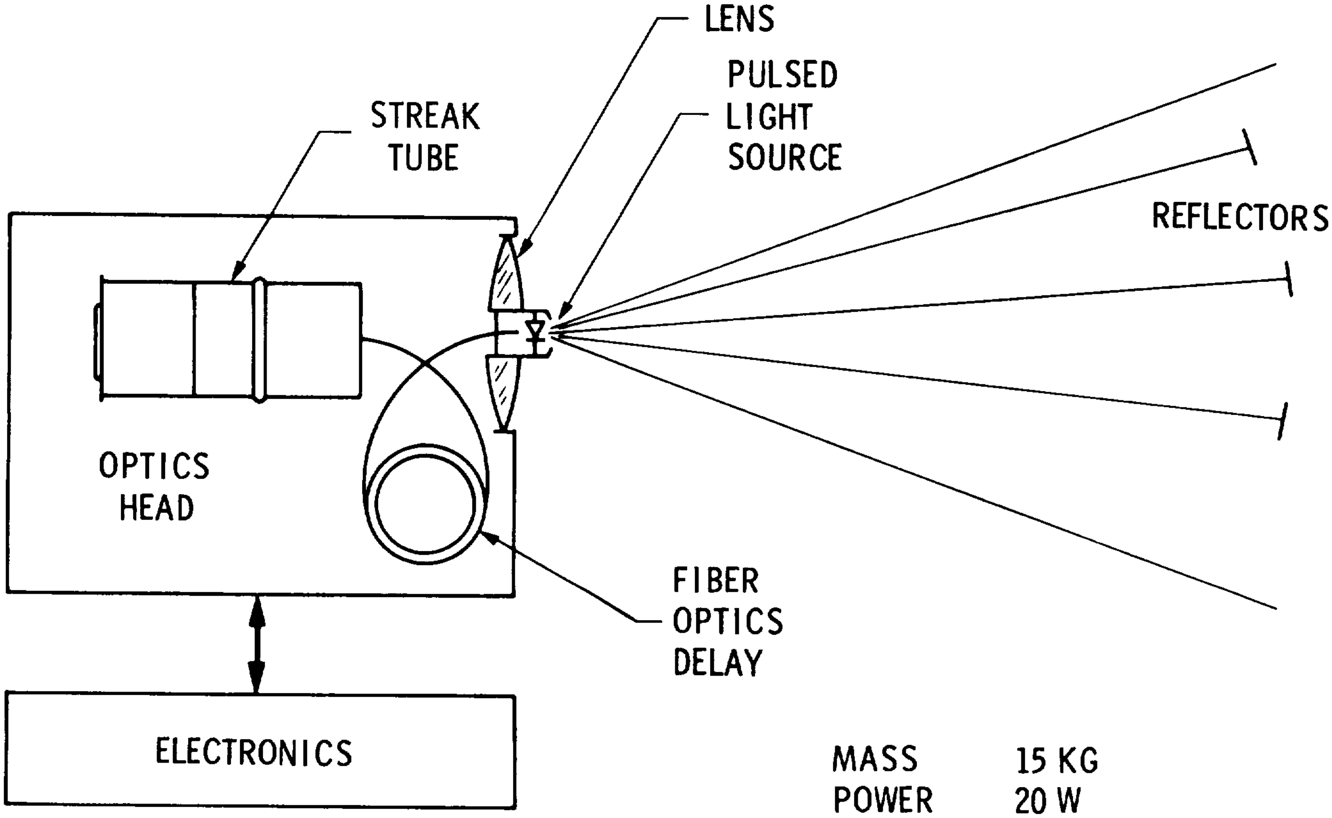


Figure 2

There are two potential pulsed laser-diode light sources for SHAPES. One uses direct modulation of the diode current to obtain the short-pulse behavior. The other uses mode locking in an external cavity. The direct modulation allows a wide range of repetition frequencies but does not give as narrow a pulse as the mode-locking configuration. Mode locking is restricted by practical cavity lengths to high repetition frequencies, but gives pulses of shorter duration. The choice of one source or the other will be influenced by the particular requirements of a given situation. Figure 3 gives some results obtained at JPL in the two configurations with diodes operating at 0.82μm. The upper curve is for a direct-modulation diode and shows a width of 28 ps (full width at half maximum). The lower curve is the output of a synchronously pumped, mode locked laser and shown a 10 ps width.

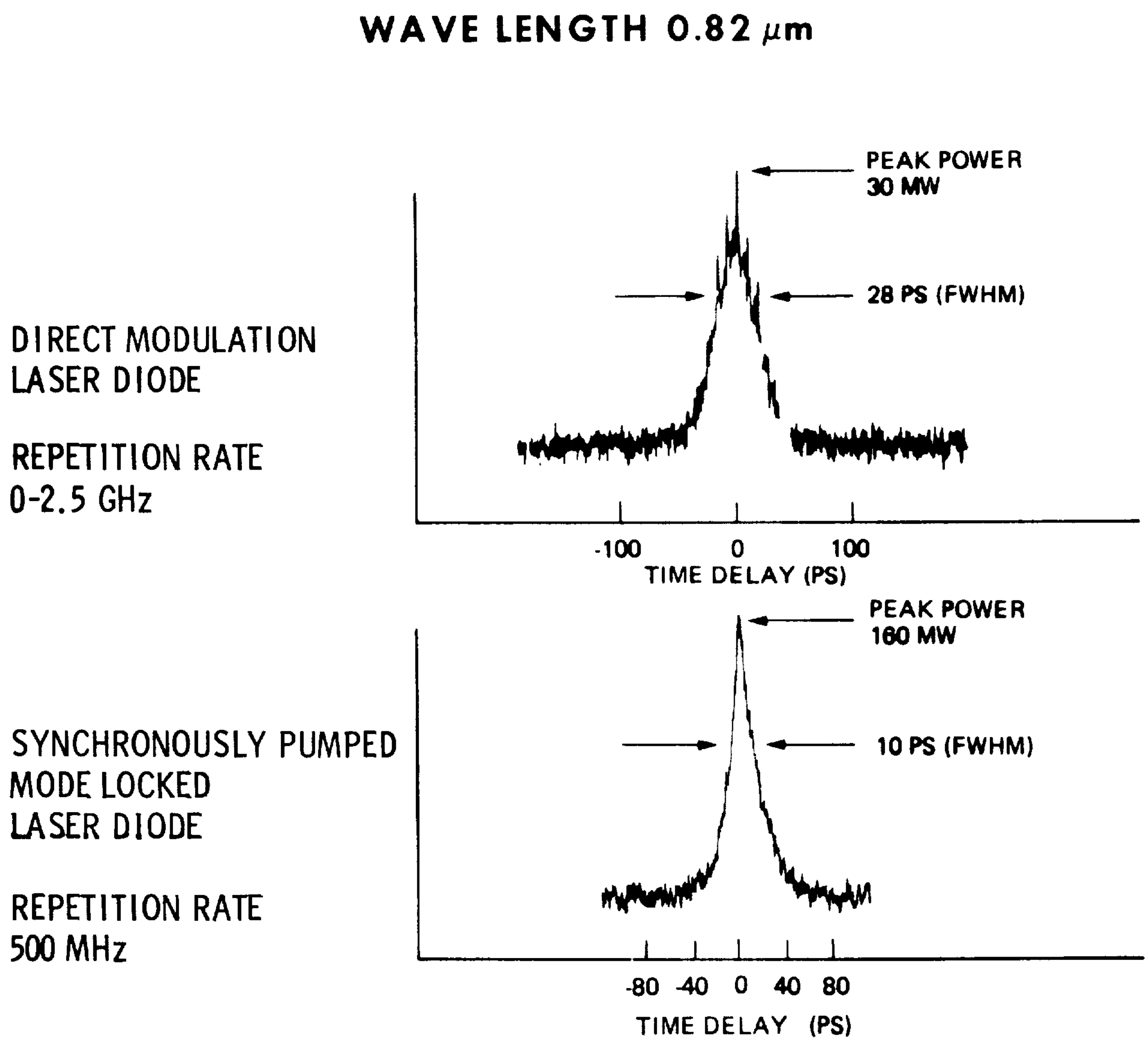


Figure 3

FIBER-OPTICS DELAY AND INTEGRATED-OPTICS WAVEGUIDE SWITCH

The fiber-optics delay which provides the reference pulse in SHAPES has two major components: the optical fibers and the integrated-optics waveguide switches. The propagation of the reference pulse through the fiber path provides the delay. The switches are used to insert or remove lengths of fiber from the path to adjust the delay to that required for the particular situation. The technology for the fibers is well developed. Fibers with losses of less than a db per kilometer are available. The temporal dispersion of the pulse as it propagates through the fiber is an important parameter, and this is of the order of 10 picoseconds per 100 kilometers.

Integrated-optics waveguide switches can be constructed using titanium-diffused lithium niobate technology. The waveguide structure is constructed by the deposition of Ti on $LiNbO_3$ through a mask. The Ti is diffused into the $LiNbO_3$ by heating in an oxidizing atmosphere changing the properties of the substrate and producing the waveguide. Metal electrodes are then deposited on the surface of the material producing a configuration as shown in figure 4. The application of a voltage to the electrodes changes the index of refraction of the $LiNbO_3$ between the waveguides thus changing the coupling between them. This technology is under development by JPL for high-data-rate communication and for the Fiber Optics Rotation Sensor (FORS). The experimental models have switching times of less than 100 ps and insertion losses of about 7 db. Improvements in the insertion loss are expected as the technology develops.

10% TO 90% RESPONSE LESS THAN 100 p sec

THIS COMPONENT IS UNDER DEVELOPMENT. PRESENT INSERTION LOSS IS 7 db. THIS IS EXPECTED TO SHOW SIGNIFICANT IMPROVEMENT WITH FURTHER WORK

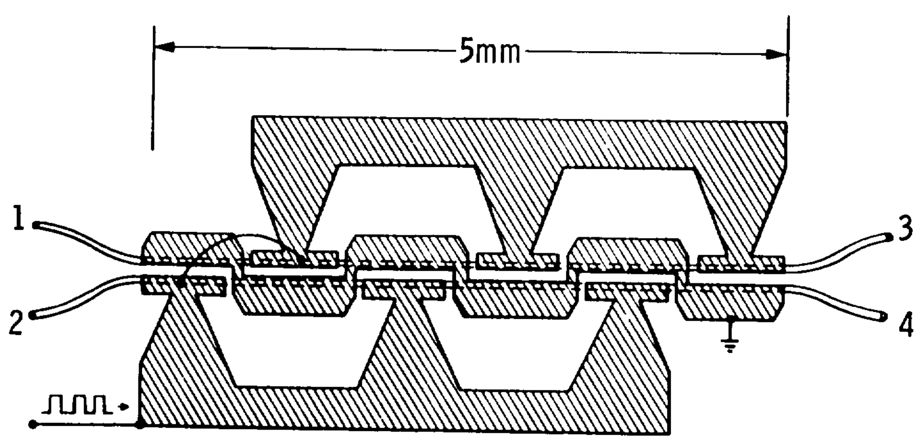
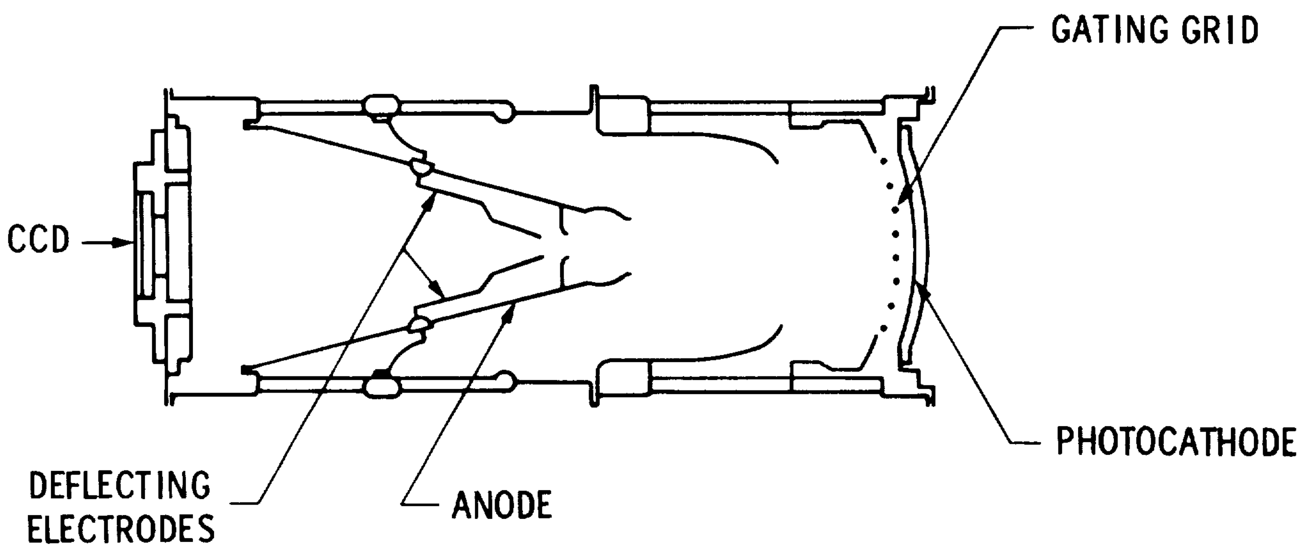


Figure 4

PICOSECOND STREAK TUBE

The streak tube which provides the fine time resolution draws on a well established technology. Streak tubes utilizing phosphor-screen output are widely used and offered by several manufacturers. CCD imaging devices are also widely used, and at least one manufacturer has produced a streak tube with a CCD output. This tube, shown in figure 5, has an S1 response photocathode (Ag-O-Cs) which has a peak close to the 0.82μm output of the laser-diode source. A typical gain (electrons out of the CCD per photon into the photocathode) is 10, and the transit-time spread is approximately 4 picoseconds. These parameters are sufficient for adequate performance of SHAPES in a number of situations. For other applications further development of the streak tube may be required.



PHOTOCATHODE	S1 (Ag-0-Cs)
GAIN $\left(\frac{\text{CCD ELECTRONS}}{\text{PHOTON}}\right)$	~10
TRANSIT-TIME SPREAD	~4p sec

Figure 5

SHAPES RANGE MEASUREMENT

Figure 6 shows the SHAPES configuration for absolute range measurement. A diverging lens is used to control the spread of the illuminating beam. Retroreflectors are used to return the radiation to the sensor head efficiently. A beam splitter is used to couple the reference pulse into the fiber and to direct onto the photocathode after passing through the fiber delay. The integrated optics switches allow the switching of varying amounts of delay into the reference path, while the streak tube provides the fine resolution of range.

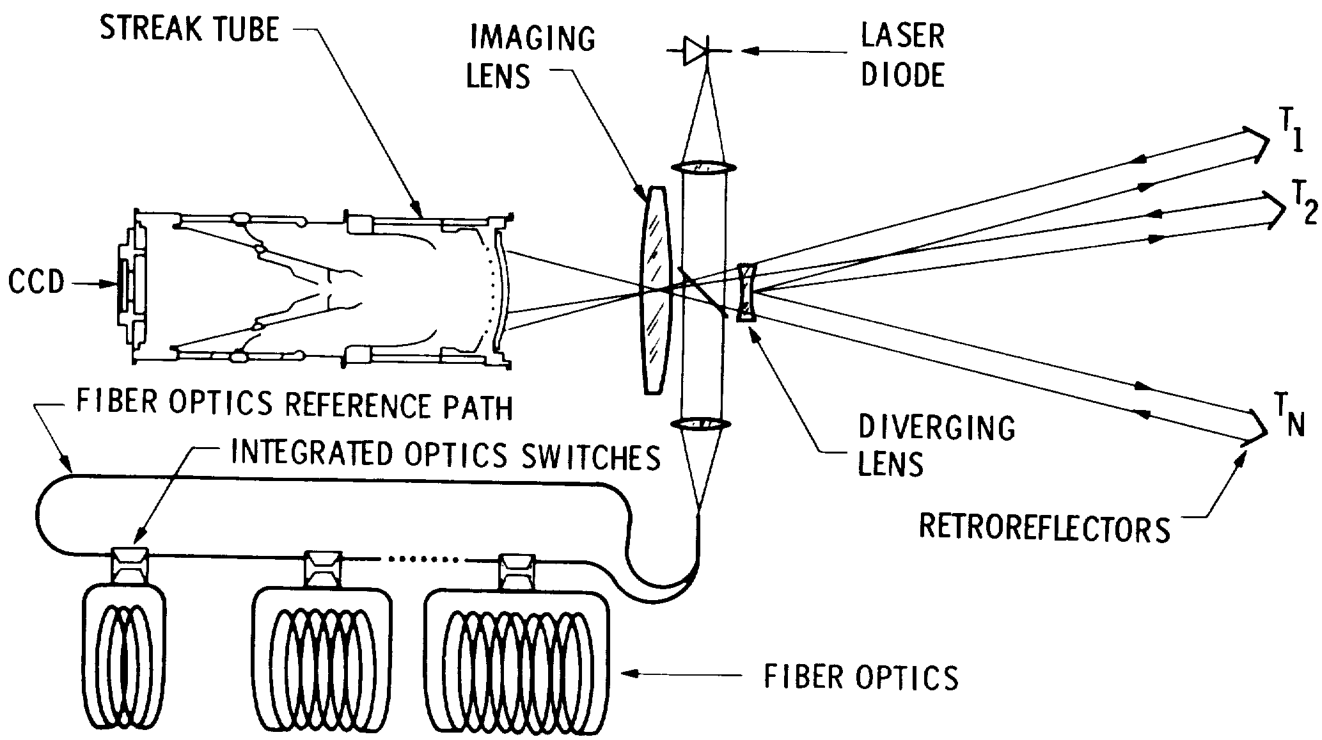


Figure 6

The images produced on the CCD detector by the electron optics of the streak tube are shown in figure 7. The circular spots are the direct images of the reflector as relayed by the electron optics with no sweep voltage applied to the deflection electrodes. The locations of these images measure the directions to the reflectors from the sensor head, and also provide the initial points for the time-delay measurements. The elongated spots are the images produced when the tube is sweeping. It is the displacement ΔZ_n of the two images (swept and unswept) of a point that is the measure of the time delay. The elongation of the swept spots is the result of the width of the pulse and the spread in electron transit time in the tube. The points in the center of the field separated by ΔZ_0 are from the reference fiber.

Each point on the CCD image is the result of an accumulation of charge from many laser pulses. The readout of the CCD is controlled and the data processed by a microcomputer. The program interpolates to find the centroid of each spot. This can be done to an accuracy of 1/100 of the spot dimension.

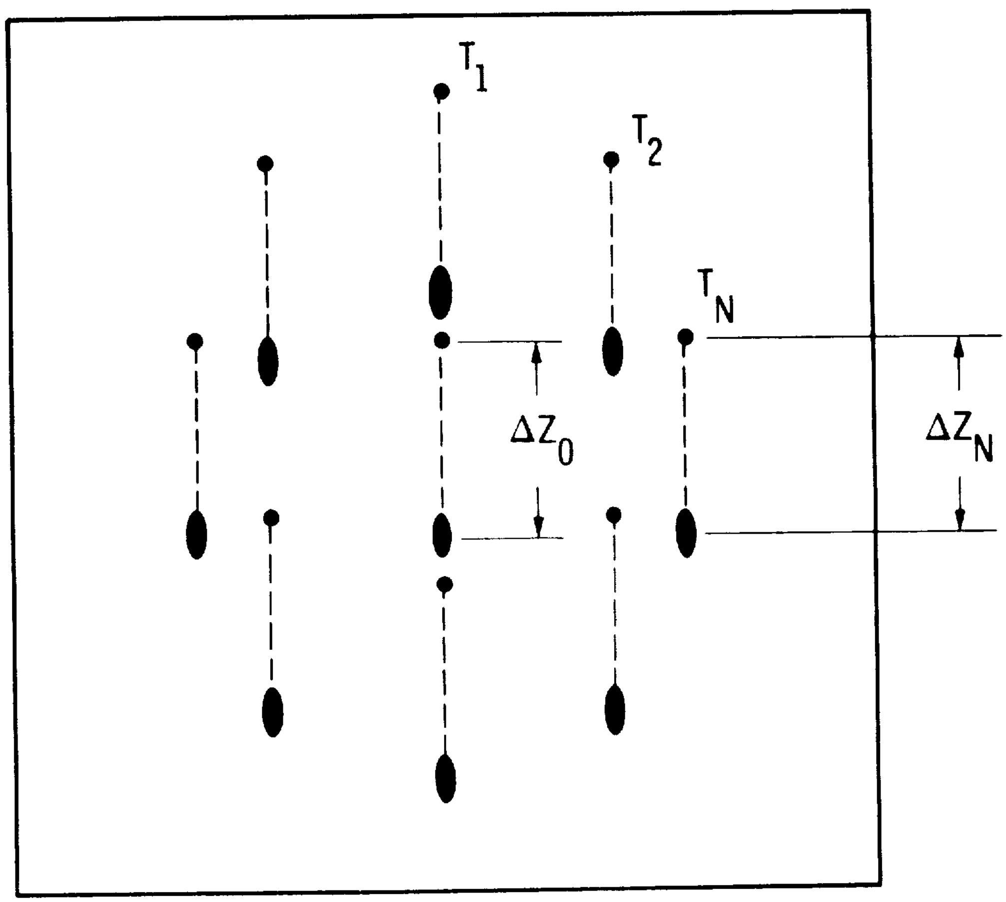


Figure 7

SHAPES RANGE MEASUREMENT

WITH HIGH-PRECISION CCD 2-AXIS ANGULAR MEASUREMENT

The precision with which the angular position of the reflector is determined can be improved by the addition of a beam splitter and second CCD as shown in figure 8. By taking the image locations from this second CCD the distortions of the electron optics of the streak tube are removed. Note that the losses of the beam splitter are partially offset because charge can be accumulated in both CCD simultaneously and only the readout needs to be time shared.

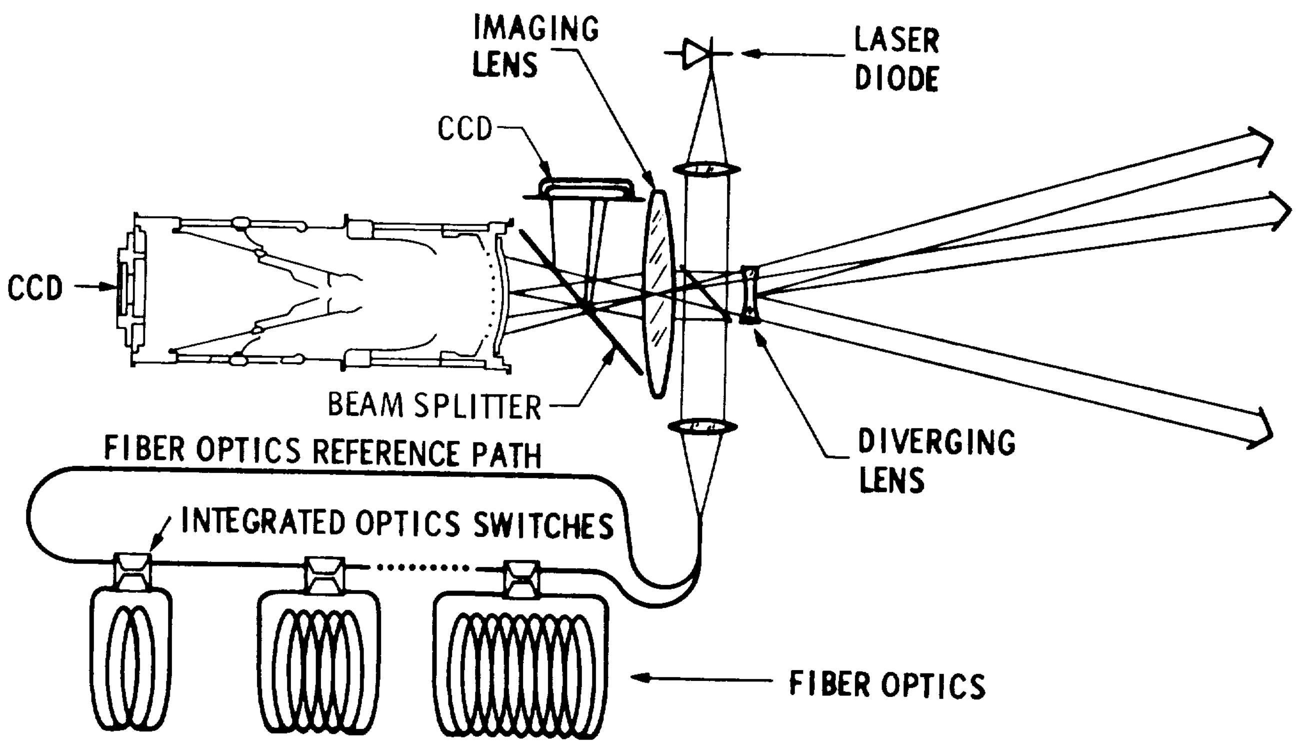


Figure 8

SHAPES RANGE MEASUREMENT WITH VERY HIGH PRECISION

CCD 2-AXIS ANGULAR MEASUREMENT

In some applications where the angular spread of the points is large, the system previously show in figure 8 reaches a limitation in that the angular motion of a given point moves the image over a very small portion of the CCD. This limitation can be overcome with the addition of image combining fiber optics and a relay lens as shown in figure 9. The image-combining optics is a set of coherent, i.e. imaging transmitting, fiber bundles. These rearrange the images of the sensed points into a more compact configuration for better utilization of the streak tube and the CCDs.

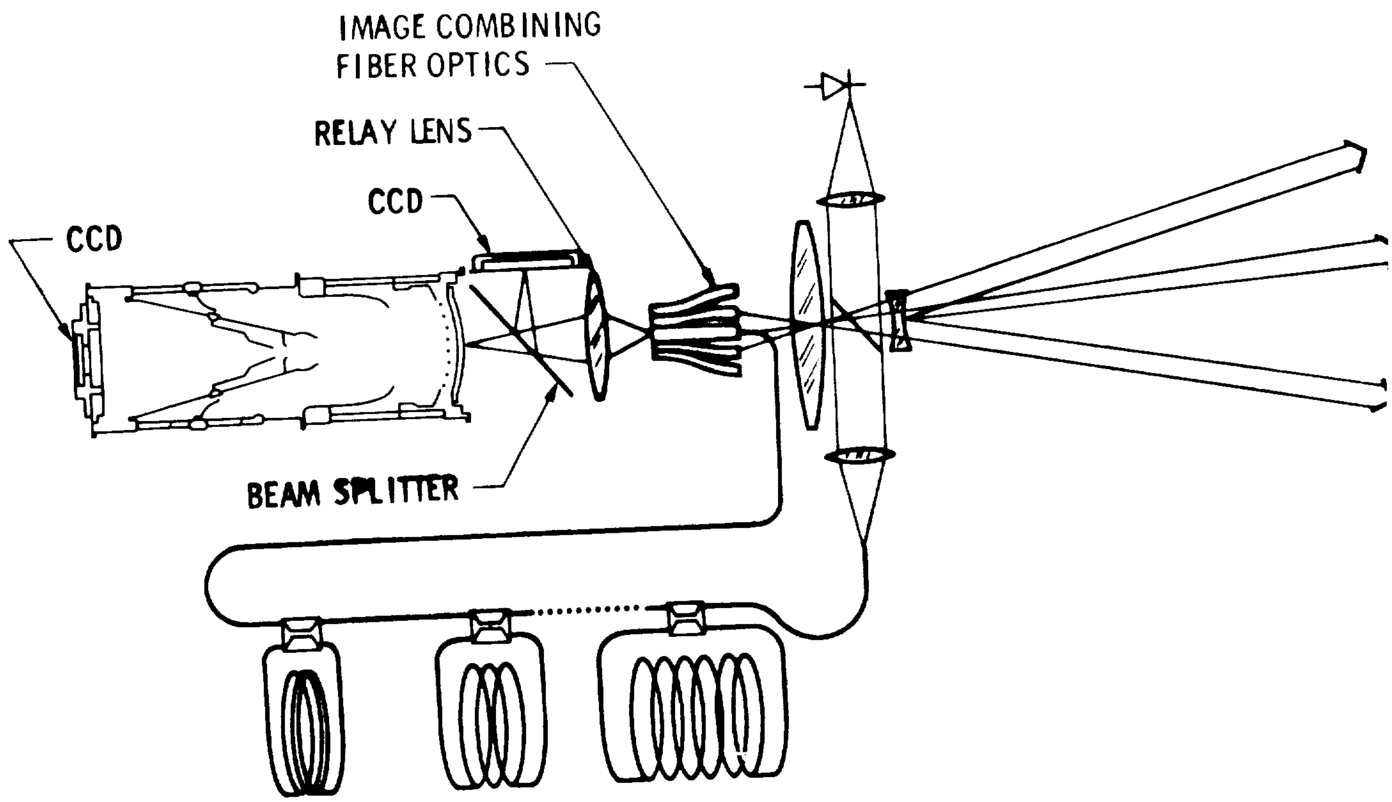


Figure 9

RANGE MEASUREMENT CCD WITH IMAGING FIBER OPTICS

The images which appear on the CCD of the streak tube when the image-combining optics are used are shown in figure 10. The principles of operation are the same as those shown in figure 7 except for the arrangement on the CCD. The interval designated ΔZ_0 is that produced by the reference fiber.

The expected performance of the SHAPES system can be summarized as follows: The accuracy of the angular measurement with full field optics is one part in 10^4. With the field-compression field optics this becomes approximately one part in 10^5. The range measurement uncertainty is about 0.15 mm. The multiple targets can be of the order of 50 and the data range up to 10 target sets per second.

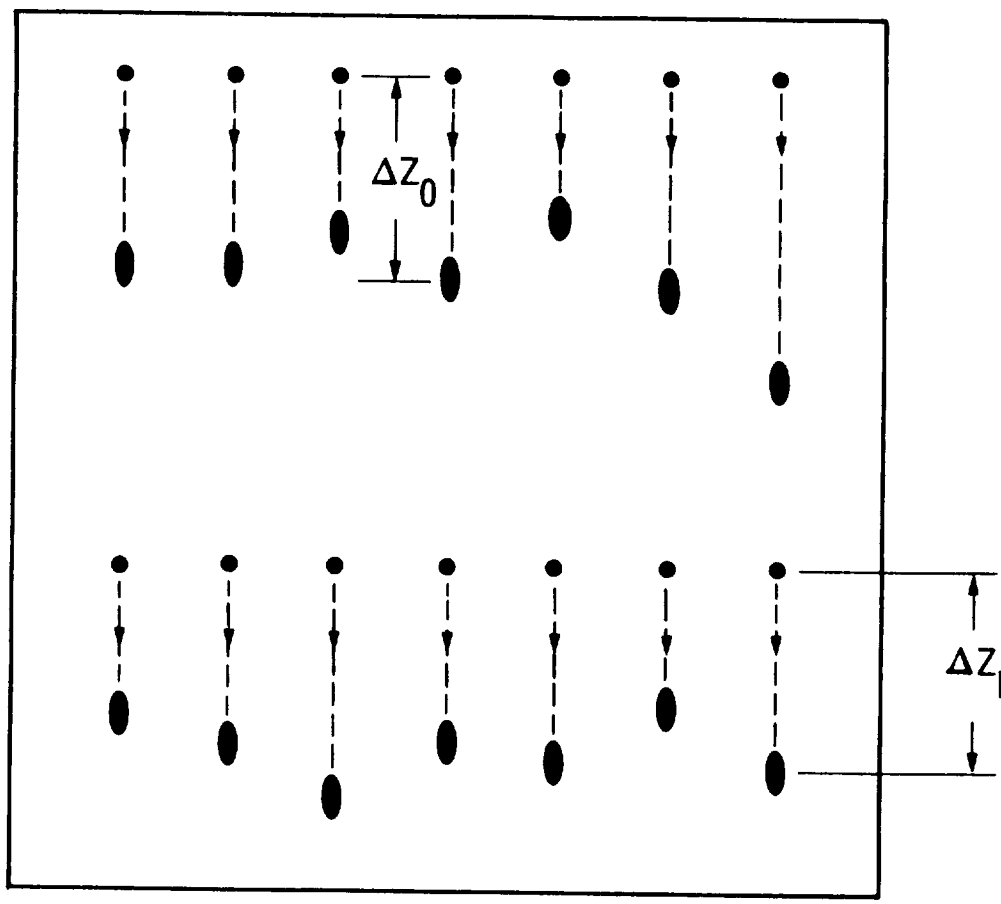


Figure 10

DEVELOPMENT STATUS OF SHAPES ENABLING NEW TECHNOLOGY

Figure 11 is a table showing the status of the various technologies re-required by SHAPES. Although they are in various states of development, all are sufficiently mature to allow work on shapes to go forward. The results for the picosecond laser diodes are ones obtained at JPL. Similar results have been obtained at other laboratories. The optical fiber used in the delay lines was developed for optical communication and is commercially available. The integrated-optics switches have been under development for some time, both high-speed data processing and transmission and for the Fiber Optics Rotation Sensor. Streak tubes with picosecond resolution are available with phosphor outputs from several manufacturers, and one manufacturer has demonstrated a tube with a CCD output. Finally, CCD's themselves have been a commercial item for several years and are available from several manufacturers.

TECHNOLOGY	STATUS
• PICOSECOND PULSED LASER DIODES	25 PS FWHM DEMONSTRATED 10 PS FWHM MODE LOCKED DEMONSTRATED
• FIBER OPTICS DELAY LINES	MATERIAL DISPERSION (@ 0.82 μm) ~10 PS/100 M
• INTEGRATED OPTICS SWITCHES	UNDER DEVELOPMENT 10 TO 90% RESPONSE <100 PS
• PICOSECOND STREAK TUBE	• COMMERCIAL PRODUCT (PHOSPHOR OUTPUT) • CCD OUTPUT DEMONSTRATED 1979
• CCD IMAGING DETECTORS	• COMMERCIAL PRODUCT

Figure 11

SHAPES APPLICATION -

POINTING AND CONTROL OF A LARGE SPACE ANTENNA

The application of SHAPES to the pointing and control of a large space antenna is illustrated in figure 12. The particular antenna shown is a possible configuration for Land Mobile Satellite Service. The antenna is of wrap-rib construction and the spacecraft bus is located at the antenna feed. The particular advantages of SHAPES for this application are: (1) It can cover the entire antenna with a single sensor head, (2) It determines the location of many points simultaneously, (3) It operates from a central location on the bus and can be co-located with star trackers, earth sensors or other attitude sensing devices. When used in this way SHAPES provided information on static shape; vibration sensing; and, when combined with the attitude sensors, the information required for antenna pointing.

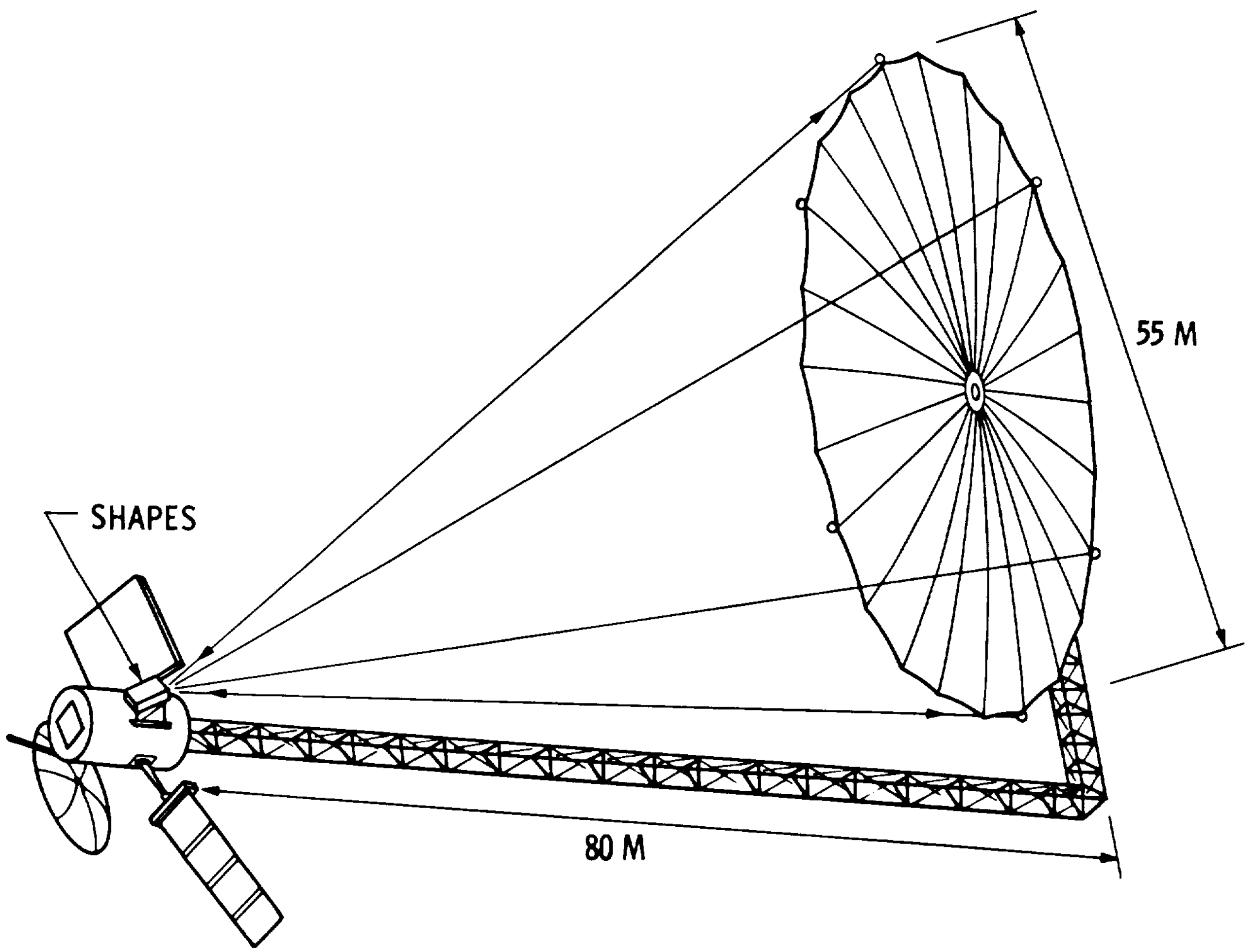


Figure 12

APPLICATION OF SHAPES TO RENDEZVOUS AND DOCKING

SHAPES can be used for the measurement of the three-dimensional position and the rotational and translational velocities in rendezvous and docking operations as shown in figure 13. The required modifications are an increased range of delays in the reference path and some autofocus capability both in the illuminating system and the imaging system.

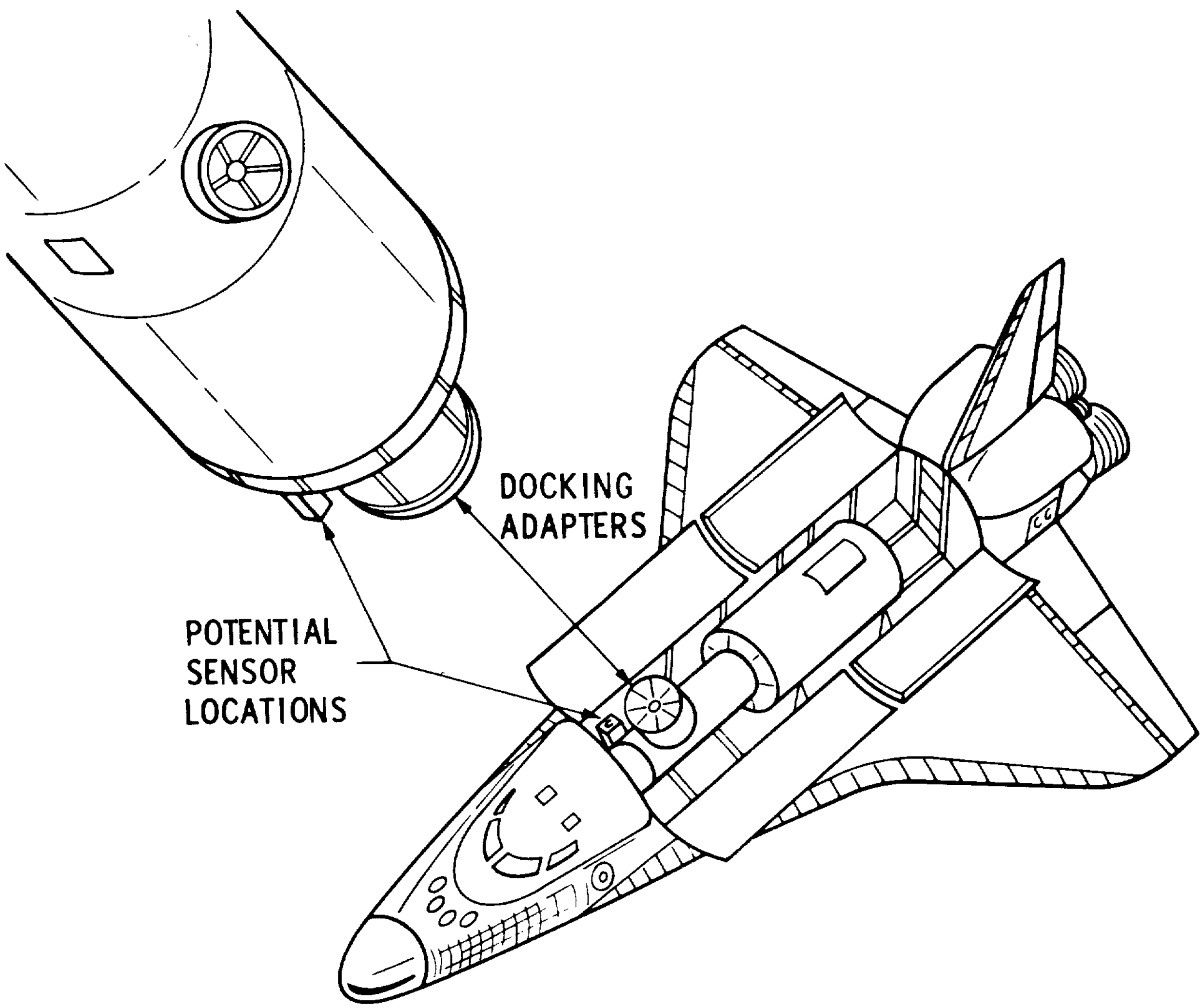


Figure 13