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SENSOR TECHNOLOGY FOR ADVANCED SPACE MISSIONS

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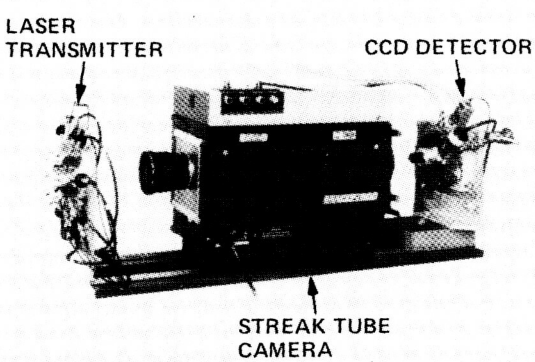
INTRODUCTION

Control systems of large space structures will require new capabilities in rapid and accurate sensing of numerous critical points on the structure in order to manage complex space operations. This paper presents a summary of the development of two sensors able to provide this capability. The first to be discussed is SHAPES, which stands for Spatial, High-Accuracy, Position-Encoding Sensor. SHAPES is an electro-optic sensor that combines optical angular position measurement with multiple light-pulse time-of-flight range measurements to provide three-dimensional position measurements. The unique characteristic of SHAPES is the capability to track multiple targets with precision at a data rate sufficient for control purposes.

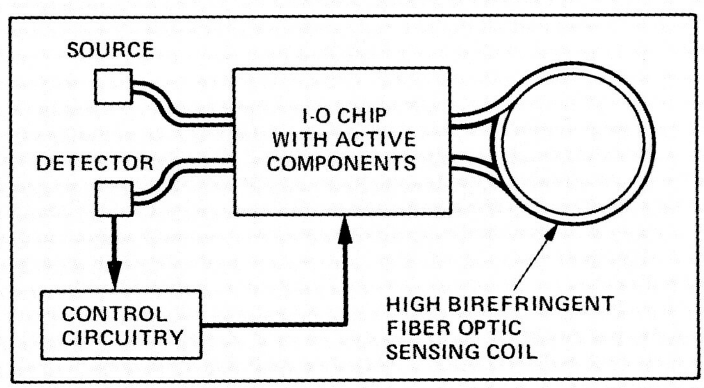
The second sensor we will discuss is FORS, an acronym for Fiber Optics Rotation Sensor. FORS is a new type of gyro that utilizes semiconductor lasers and fiber optic waveguides, together with a unique integrated optics (IO) multifunction optical circuit design for optical signal processing. One of the most significant characteristics of FORS is the capability of very long life provided by solid-state components. Additional advantages are low weight and cost. In addition to its application as a precision navigation-grade gyro, FORS can be configured for monitoring many points of a large space structure by using miniature remote gyro heads connected with optical fiber to a central FORS signal processor.

SHAPES



- 3-DIMENSIONAL POSITION MEASUREMENTS
- MULTIPLE TARGETS
- 10 MEASUREMENTS/SEC
- SUBMILLIMETER ACCURACY

FORS

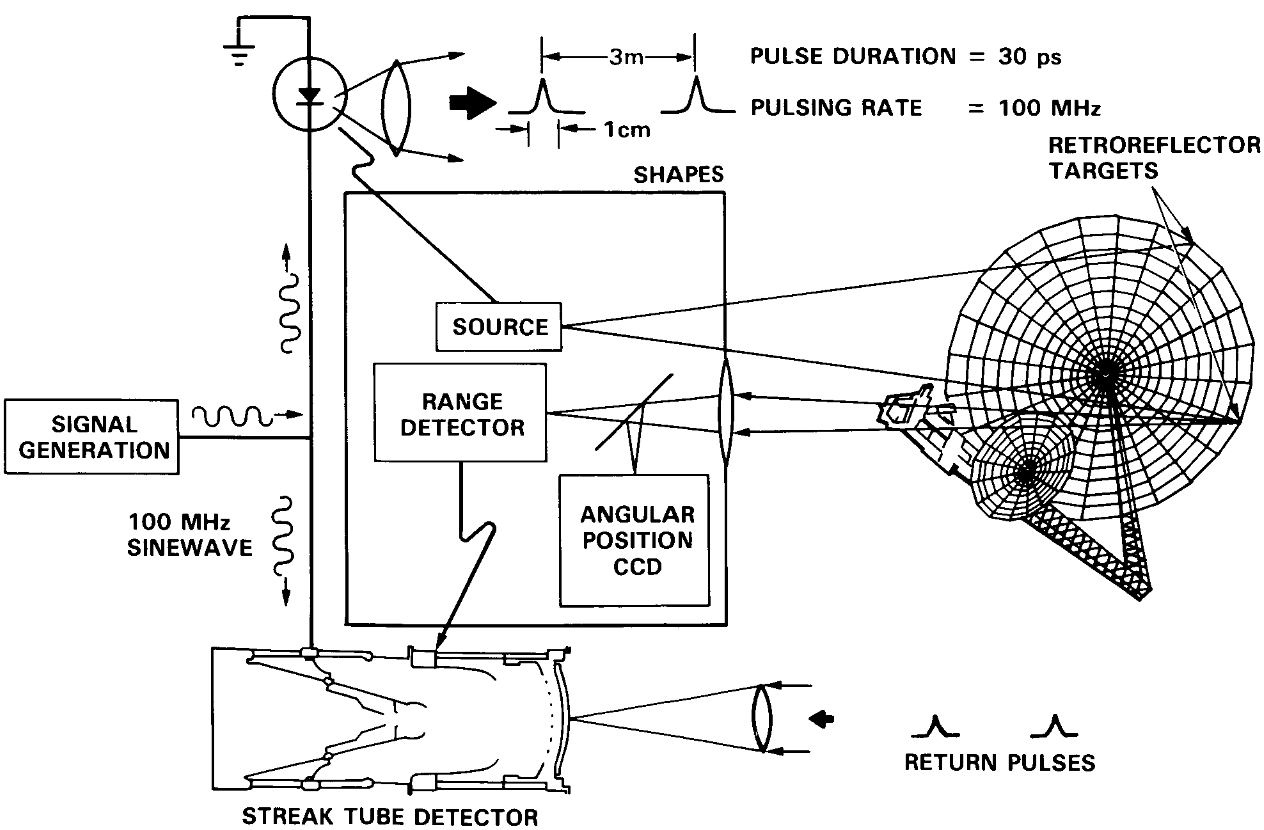


- LONG LIFE (ALL SOLID-STATE)
- LOW COST
- LIGHT WEIGHT

SHAPES OPERATING PRINCIPLE

The SHAPES operating principle is illustrated below. A continuous stream of optical pulses is directed to the target area and illuminates a number of points designated by retroreflectors. The return pulses are imaged onto the streak tube range detector. Time resolution is provided by the streak tube deflection plates as in an oscilloscope, and range is determined by correlation of the time-of-flight of the laser pulses with the deflection plate voltage. Angular position of each point will be obtained by imaging part of the returned light onto a CCD array detector. The well established CCD star tracker technology will be used for the angular position measurement.

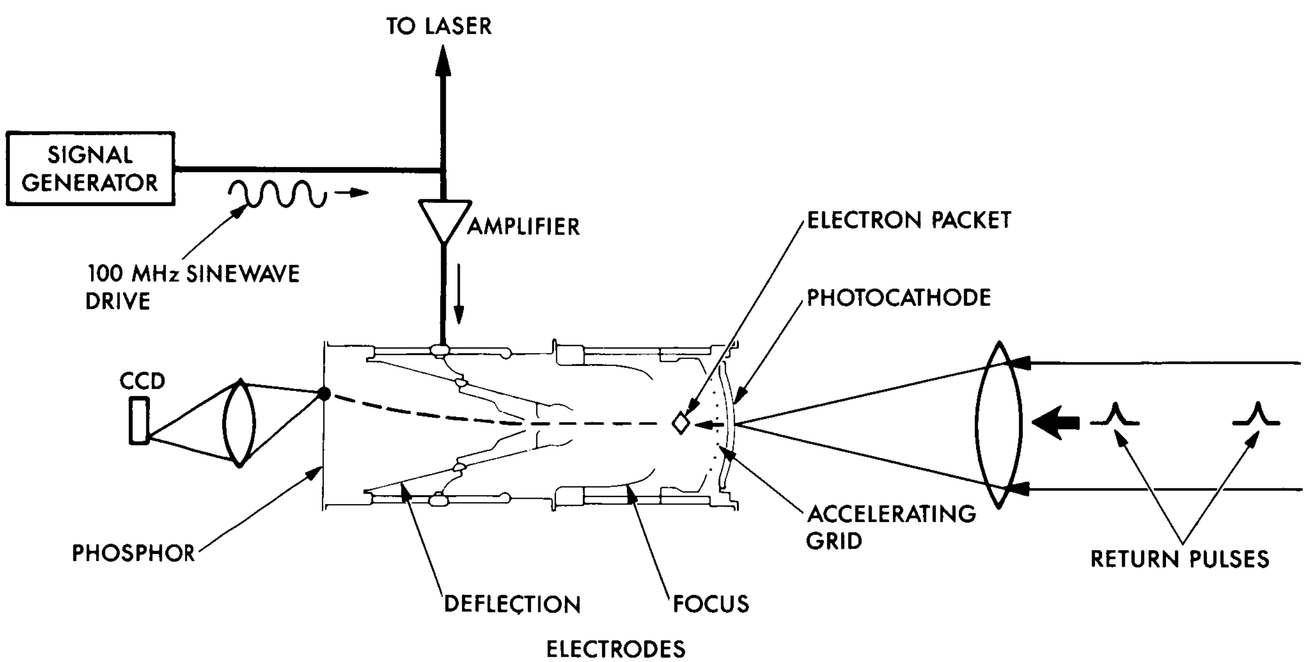
Very short laser pulses are required for accurate range measurement. The present experiment utilizes 780 nm laser diodes which are driven by short (80 ps) current pulses to produce 30 ps optical pulses. When operated at 100 MHz, the average output power of each laser is about 0.25 mw and the light pulses are separated by 3 m as indicated below.



RANGE MEASUREMENT WITH A STREAK TUBE

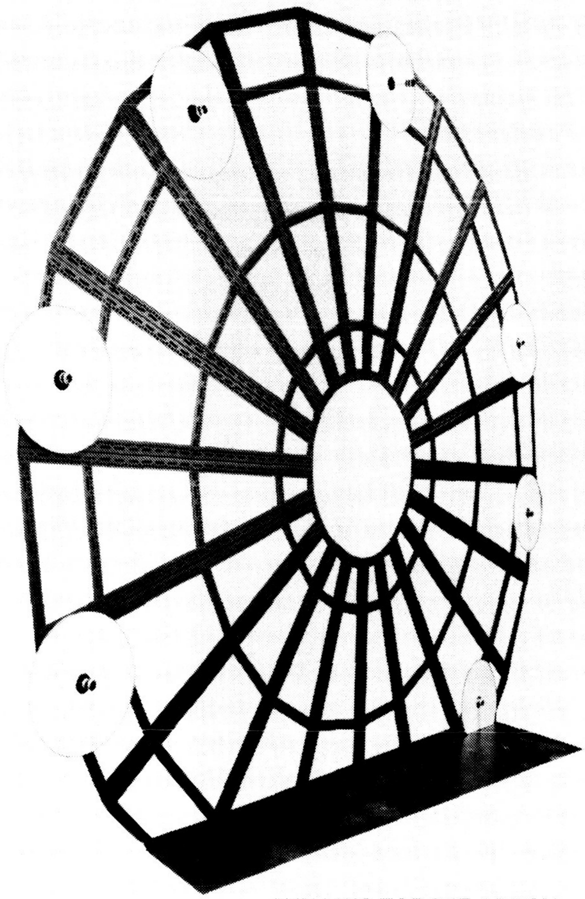
Photoelectrons are produced at the streak tube photocathode by each returning optical pulse. The electrons are accelerated by a high-voltage grid, directed between the deflection plates by focusing electrodes and finally impinge on a phosphor screen. The fluorescent images of each target on the screen are then transferred to a CCD for readout. The deflection plate voltage is synchronized with the output laser pulse so that the electron packets formed from all optical pulses reflected from an individual target during each framing sequence will strike the phosphor at the same point. Thus each image point on the CCD is the result of the accumulation of charge from many laser pulses. This allows the use of relatively low-powered sources since it is not necessary to detect the signal from a single return pulse. A typical exposure time of 10 ms for each frame results in the integration of 10^6 pulses on the CCD.

The readout of the CCD is controlled by a microcomputer that also processes the data to determine the centroid of each spot and provide usable output. Centroids are determined to an accuracy of about 1/100 of a CCD pixel. The framing rate depends on the target exposure time per frame and the number of targets. For example, a framing rate of 10 Hz with eight targets corresponds to an exposure time of 10 ms.

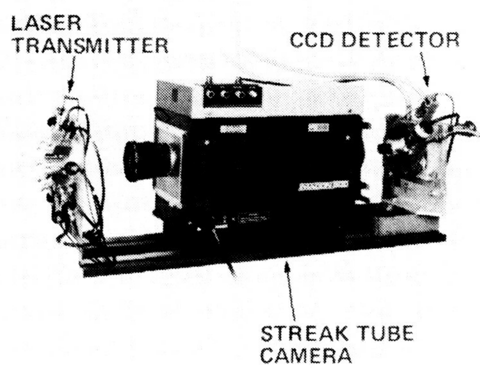


SHAPES TEST FACILITY

The SHAPES Test Facility was designed to demonstrate the sensor's capability to simultaneously track multiple moving targets with high precision. A 4-m-diameter structure was built to support the moving targets in a circular arrangement that simulates an antenna application. The SHAPES sensor was located in an adjoining room, 12 m from the target array. Shown below are an array of laser sources, a commercial streak-tube camera, and the CCD assembly. The individual components of the sensor have been separated for easy viewing. Not shown are the custom electronics used to read the CCD and the microcomputer used to control the system.

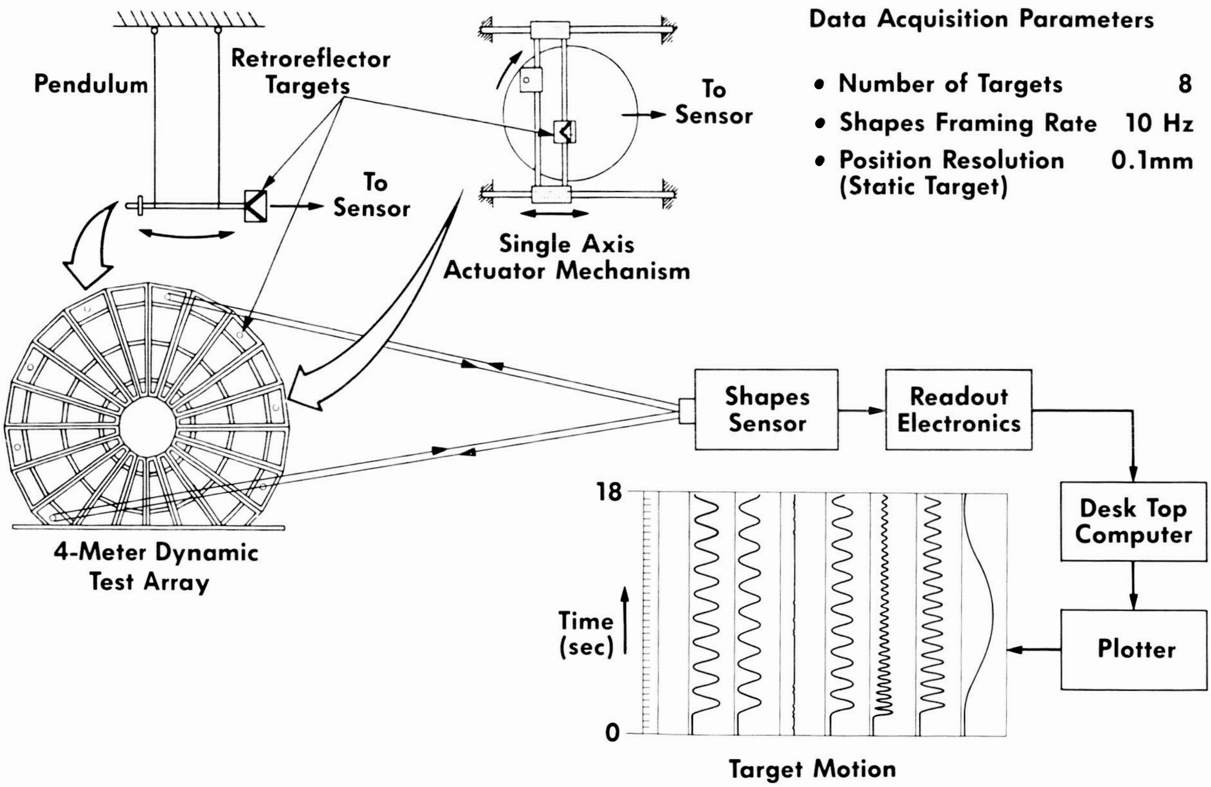


DYNAMIC TARGET ARRAY



MULTITARGET DYNAMIC RANGE DEMONSTRATION

In a recent laboratory demonstration of the ranging capability of SHAPES, the range to each of eight moving targets was measured simultaneously. The targets were mounted on the 4-m-diameter SHAPES Test Facility described previously. Target motion was provided by mounting the retroreflectors on either free-swinging pendulums or on motor-driven actuators. For the demonstration, eight individual lasers were mounted symmetrically around the periphery of the collecting lens of the streak tube and pulsed simultaneously in synchronism with the streak-tube drive. Each laser was used to illuminate a single target. The data were processed to produce a plot of the target movement as indicated below. The framing rate for eight targets was 10 Hz with a relative range accuracy of 0.1 mm. This data update rate is sufficient for most control system requirements.



Data Acquisition Parameters

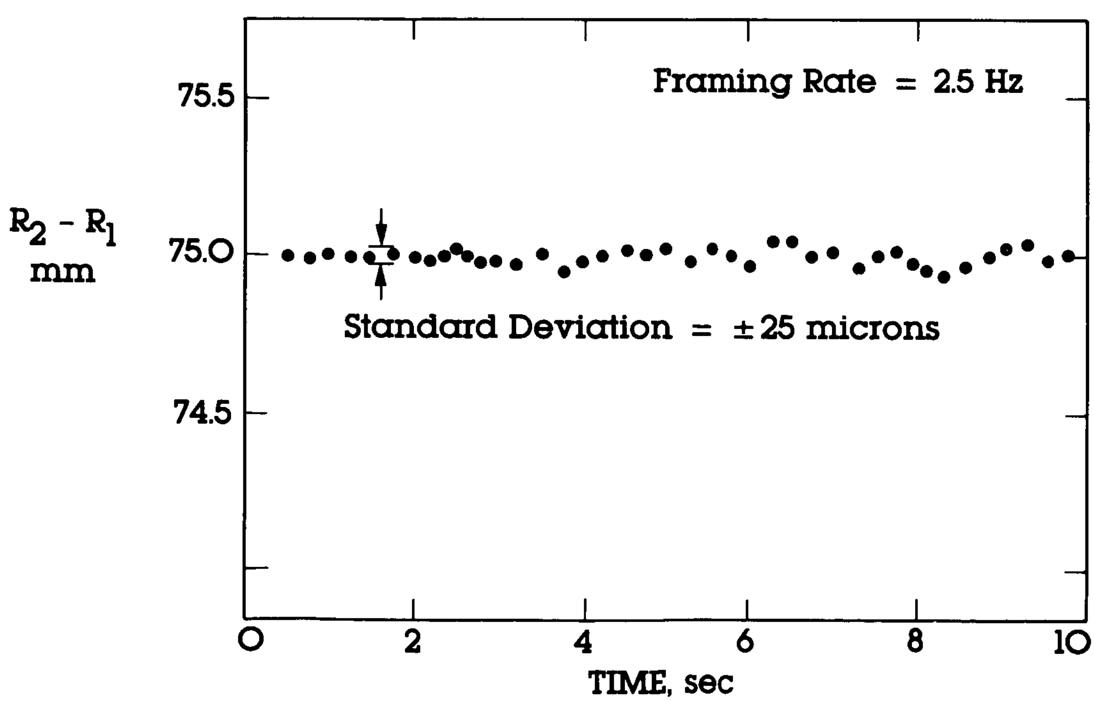
- Number of Targets 8
- Shapes Framing Rate 10 Hz
- Position Resolution (Static Target) 0.1mm

RANGE RESOLUTION

The resolution of range measurements to static targets was determined in a separate experiment. Two stationary target retroreflectors were located a known distance apart and illuminated with a single laser. The centroids of the CCD images of both targets were determined and subtracted. Based on a sample of 50 consecutive measurements, standard statistical methods were used to determine a standard deviation of 0.025 mm as indicated in the figure. The known separation of the target is used to obtain the streak-tube calibration factor.

All of the SHAPES range measurements are made relative to a reference. The reference may be provided by a calibrating target located in the sensor field of view, or it may be provided by a calibrated length of optical fiber internal to the sensor. In addition to providing range accuracy, the reference also improves the range resolution by removing much of the effects of the phase jitter and frequency drift of the drive signal that is common to the signal returns from both the reference and the target.

Experiment to Measure Range Resolution. Separation of T_1 and T_2 was Fixed at 75 mm to Obtain Streak Tube Calibration Factor.



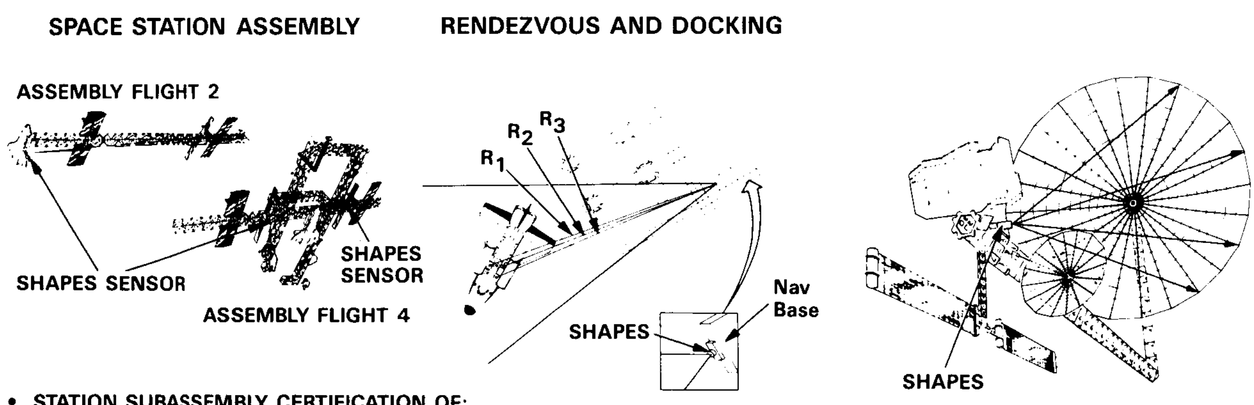
APPLICATIONS OF SHAPES

Simultaneous multitarget tracking capability is required to determine both static and dynamic in-flight characteristics of large space platforms, Space Station, and large antennas. During assembly of space structures, SHAPES measurements can be used to check static structural alignment and overall geometry during each assembly phase. After assembly has been completed, the SHAPES sensor can verify preflight structural analysis and provide the data needed to update the accuracy of models used to design attitude control and payload pointing systems. SHAPES could also be a low-cost optical system for determining absolute payload pointing from navigational base information. The center figure below shows the use of SHAPES in proximity operations where SHAPES can be used to measure relative range and attitude and their rates of change as well as the 3-D location.

The application of SHAPES to the pointing and control of a large space antenna is illustrated on the right of the figure below. SHAPES is shown operating from a central location on the bus where it is collocated with star trackers, earth sensors, or other attitude sensing devices. SHAPES is able to cover the entire antenna with a single sensor head and determine the location of many points simultaneously. This information can then be used to determine static shape, to do modal sensing and control, and, when used with the attitude sensors, to provide enhanced pointing stability and accuracy.

SPACE STATION APPLICATION OF SHAPES

LARGE ANTENNA POINTING AND FIGURE CONTROL



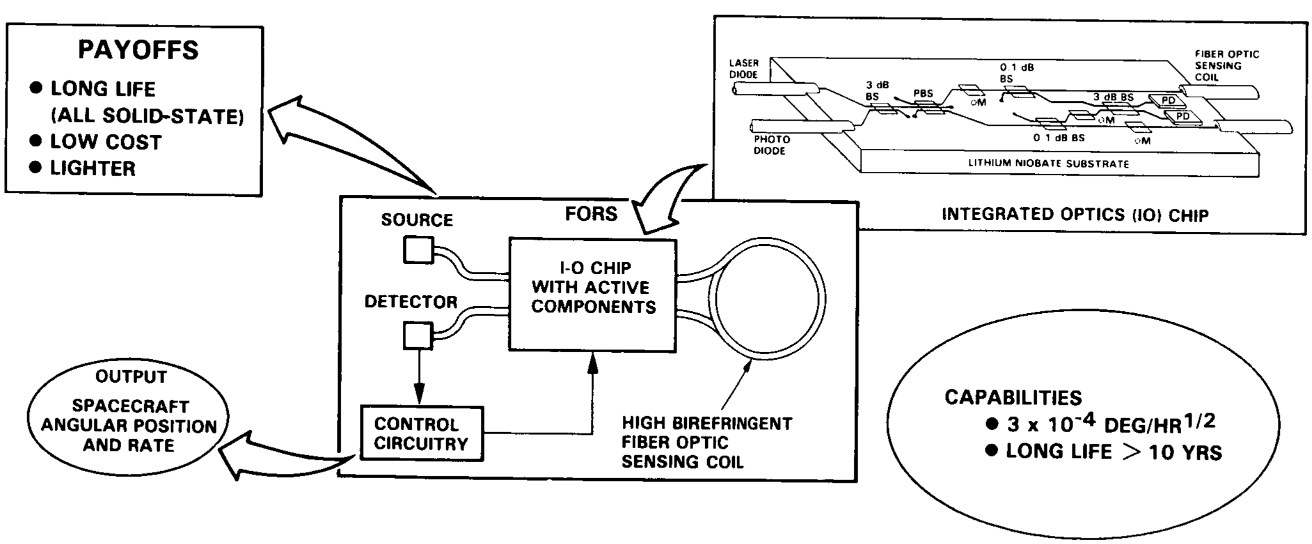
- STATION SUBASSEMBLY CERTIFICATION OF:
  - ALIGNMENT
  - GEOMETRY
  - DYNAMICS

Measurements
- Range
- Bearing
- Attitude
- Rates

FIBER OPTIC ROTATION SENSOR

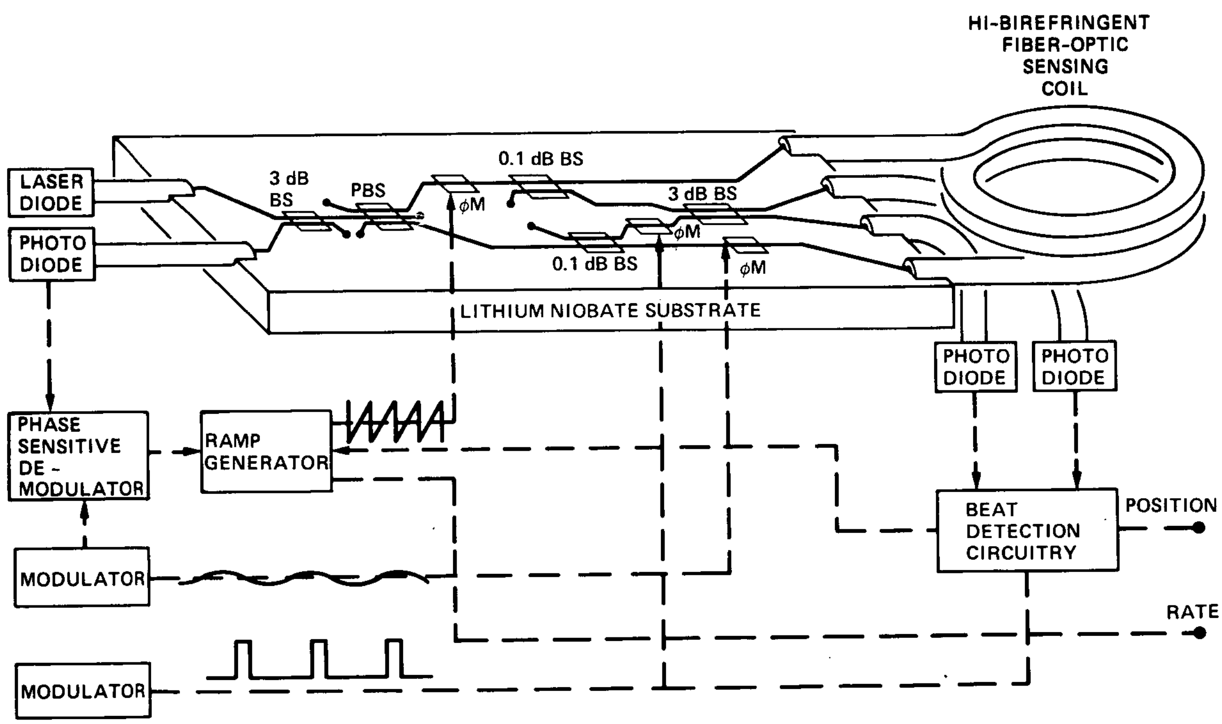
The objective of the FORS program is to develop a long life (>10 years), low cost, low weight, high reliability, navigational-grade optical gyroscope for use in future space systems. The gyroscope is being built using semiconductor lasers, fiber-optic waveguides and integrated optics waveguide circuitry for optical signal processing. The drift rate of FORS is expected to be less than .001 degrees/hr.

The operating principle of FORS is based on the Sagnac effect. A laser beam is divided on the IO chip and the two waves counter-propagated through the fiber optic coil and then recombined. Rotation of the coil results in a phase shift of one wave relative to the other. The phase shift, which is proportional to coil rotation, can be measured very accurately.



FIBER OPTIC ROTATION SENSOR WITH FULLY INTEGRATED IO CHIP

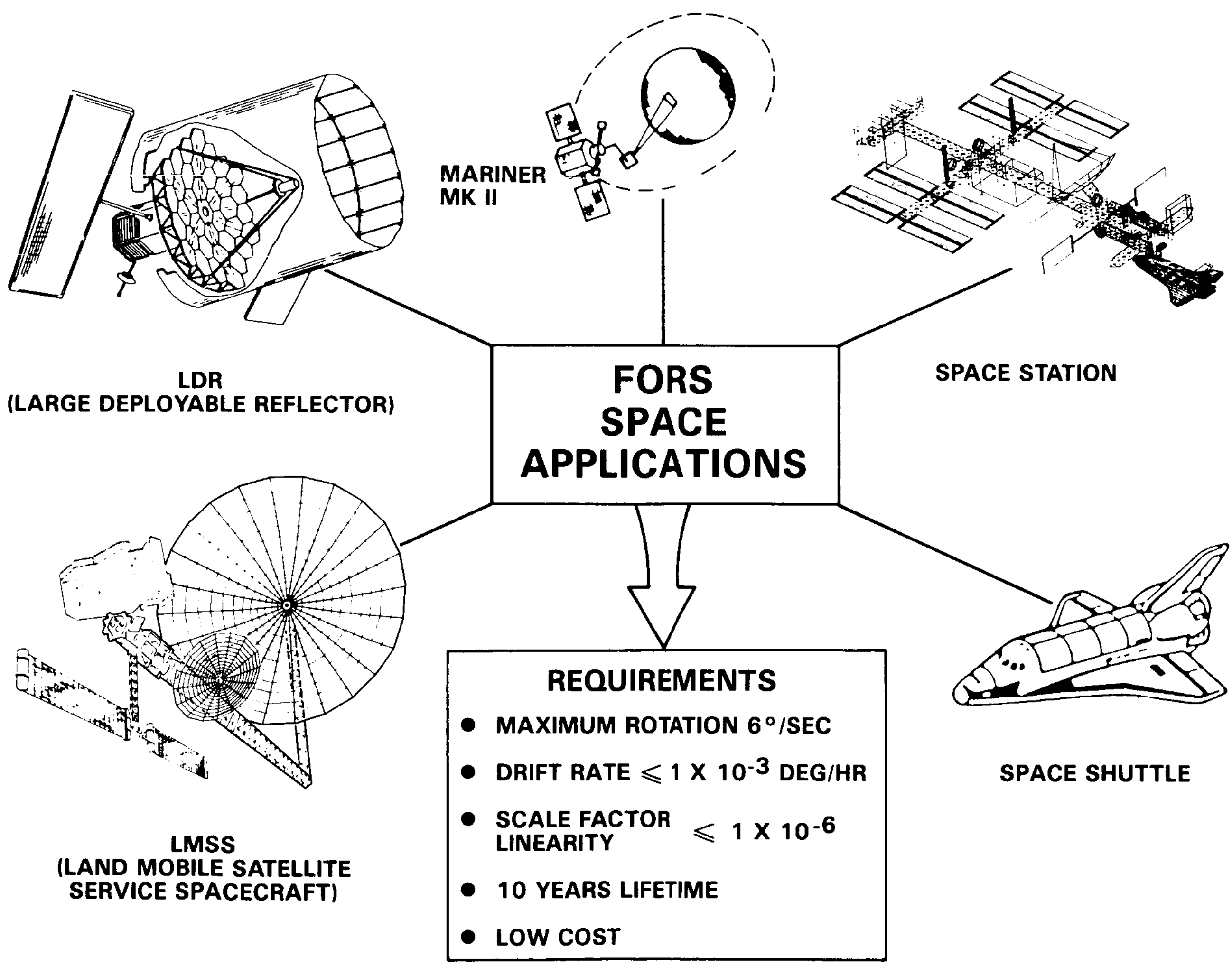
The fiber gyro design under development is shown below. It utilizes a semiconductor laser, photodetectors, fiber optic waveguide for the sensing coil, and a unique integrated optics (IO) multifunction optical circuit designed for optical signal processing. This IO configuration has an element which provides the dual function of polarizing and beam splitting (PBS). The IO chip also includes an optical phase modulator (ϕM) for use in a serrodyne closed-loop phase control providing operation over a wide range of rotation rates. The output signal is obtained by reading the optical frequency necessary for Sagnac phase nulling directly through the use of a Mach-Zehnder (M-Z) interferometer that is constructed by tapping off from the arms of the Sagnac interferometer. The M-Z interferometer provides incremental position angle by means of beats as in a ring laser gyro. In this design, utilizing the closed-loop phase nulling technique, the effect of any scale factor nonlinearity is greatly reduced and the auxiliary electronics are simplified. The complete IO circuit fits on a 5 cm long lithium niobate chip. The IO chips are under development at AT&T for JPL.



ORIGINAL PAGE IS
OF POOR QUALITY

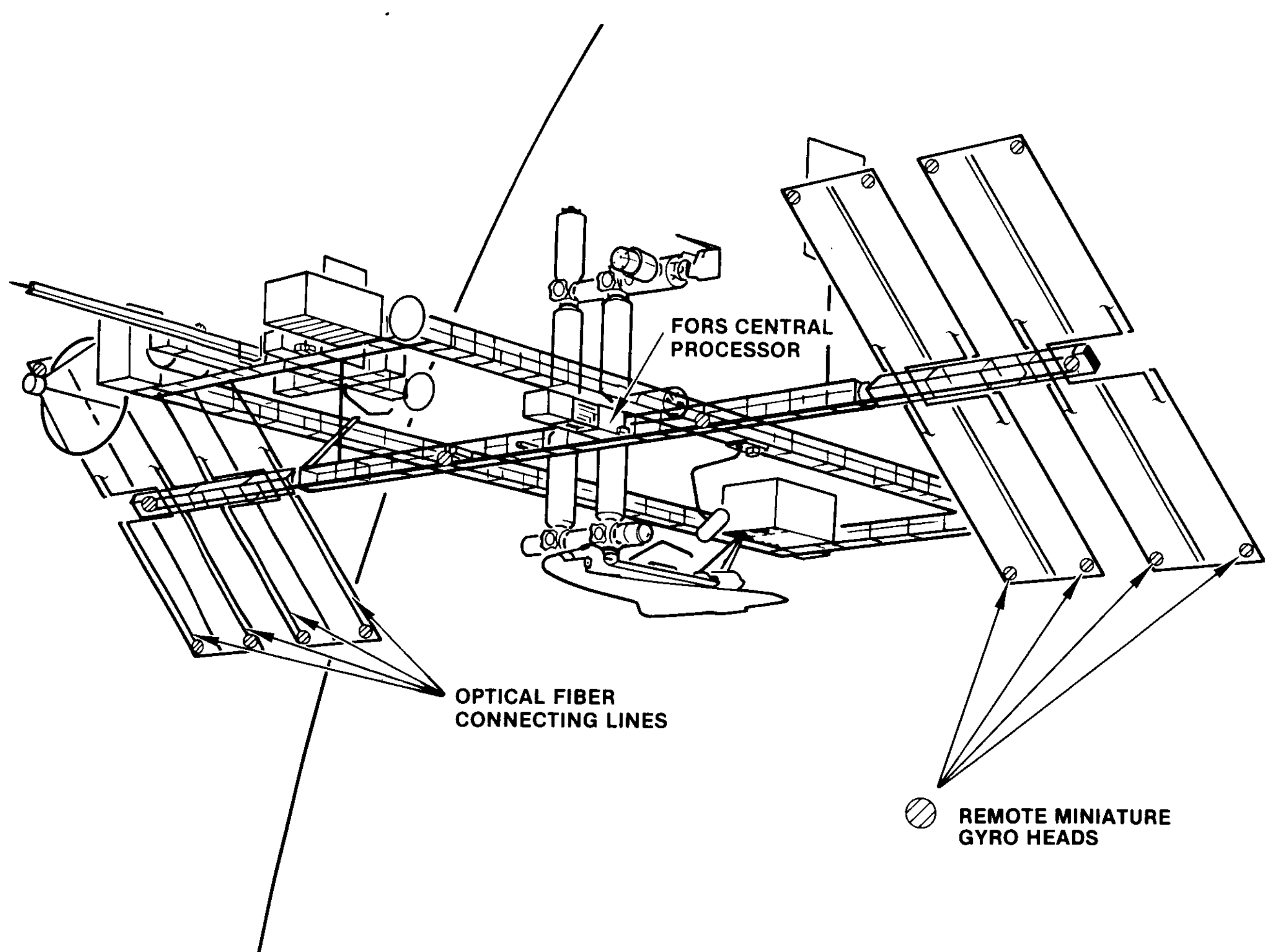
SPACE APPLICATIONS OF FORS
LONGLIFE, NAVIAGATION-GRADE IRU

The Fiber Optic Rotation Sensor is designed for inertial device applications in future space missions. The sensor can satisfy most future performance requirements while offering the potential for low weight, low cost, and long life. FORS is presently the baseline sensor for the Mariner Mark II planetary spacecraft planned for launch in 1992. For this mission, the performance requirements include drift rate of less than 1×10^{-3} deg/hr and a maximum rotation rate of 6 deg/s.



SPACE APPLICATIONS OF FORS (Continued)
DISTRIBUTED SENSING OF LARGE SPACE STRUCTURES

The FORS can be configured into a sensing system that offers the unique flexibility of placing remote miniature rotation sensing coils at many different points of a large structure. These fiber optic coils are connected with optical fibers to a central FORS sensor unit which contains the integrated optics, lasers, detectors, and required electronics to process the information. Coils as small as 3 cm in diameter are feasible. These lightweight coils, connected to the central processor, are capable of measuring angular rotation and angular acceleration of multiple remote points distributed throughout the structure and can provide a means to characterize structural dynamics and to control vibrational modes. FORS could also be used to determine the dynamics of localized Space Station payloads.



SUMMARY

This paper discussed the capability and applications of two sensors, SHAPES and FORS, for advanced missions. The multiple target, 3-D position sensing capability of SHAPES meets a critical technology need for many developing applications. A major milestone of the SHAPES task was completed on schedule on May 30, 1986, by demonstrating simultaneous ranging to eight moving targets at a rate of 10 measurements per second. The range resolution to static target was shown to be 25 microns. SHAPES scheduled technology readiness will support the sensor needs of a number of early users, some of which are listed below. The next phase in the development of SHAPES is to incorporate an angular measurement CCD to provide the full 3-dimensional sensing. A flight unit design and fabrication can be complete by FY 89.

FORS, with its significant improvement over present technology in lifetime, performance, weight, power, and recurrent cost, will be an important technology for future space systems. Technology readiness will be demonstrated with a FORS brassboard with fully integrated IO chips by FY 88. The unique capability of miniature remote sensing heads, connected to a central system, will open up new areas in control and stability of large space structures. This application requires additional study.

SHAPES

- MULTIPLE TARGET, 3-D POSITION SENSOR CAPABILITY IS CRITICAL NEED FOR MANY APPLICATIONS
- MULTITARGET RANGING DEMONSTRATED
  - EIGHT MOVING TARGETS
  - DATA UPDATE RATE OF 10 Hz
  - RESOLUTION 25 MICRONS
- SHAPES TECHNOLOGY CAN SUPPORT
  - SPACE STATION
  - COFS EXPERIMENTS
  - MSAT EXPERIMENTS
  - RENDEZVOUS AND DOCKING
  - MARS SAMPLE RETURN
  - GROUND ANTENNA POINTING

FORS

- A NAVIGATIONAL-GRADE SOLID-STATE GYRO PROVIDES SIGNIFICANT IMPROVEMENTS IN:
  - LIFETIME
  - PERFORMANCE
  - WEIGHT
  - POWER
  - RECURRENT COSTS
- HAS THE INHERENT SENSOR CONFIGURATION FLEXIBILITY OF UTILIZING MINIATURE ROTATION SENSING COILS LOCATED THROUGH A LARGE SPACE STRUCTURE
- FORS TECHNOLOGY CAN SUPPORT
  - MARINER MARK II MISSIONS
  - SPACE STATION
  - LMSS SPACECRAFT
  - ADVANCED TRANSPORTATION
  - AEROSPACE VEHICLE
  - ADVANCED ROBOTICS SYSTEMS