CONSTRUCTION ALIGNMENT SENSOR FEASIBILITY DEMONSTRATIONS (LASER MEASUREMENT)

R. H. Anderson
Lockheed Missiles and Space Company

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ABSTRACT

Lockheed Missiles and Space Company (LMSC) is developing a family of laser heterodyne sensors for use in the active control of spacecraft structures. These sensors include a HeNe distance measuring system for structures requiring accuracies to 0.1 mm and a CO_2 distance measuring system which will measure unambiguously down to 0.01 μm. Vibration sensors, based on both HeNe and CO_2 lasers, are also being developed. These systems will measure fractions of a μm displacement from DC to kHz. All of these sensors have been breadboarded to verify performance and are in various stages of development directed toward prototype engineering models. This paper discusses the design theory and trade-offs required for instrument selection.

PRESENTATION OUTLINE

INTRODUCTION

COARSE MEASUREMENTS

FINE MEASUREMENTS

VIBRATION MEASUREMENTS

TEST RESULTS

CONCLUSIONS

INTRODUCTION

For several years, the Sensor Technology Organization at Lockheed Missiles and Space Company (LMSC) has been developing sensors to be used for the measurement and active control of spacecraft structures. These sensors are all laser heterodyne systems. Both HeNe and CO_2 lasers have been used.

A coarse system, which is designed for applications where high accuracy is not required, uses a modulated beam and a high accuracy phase measurement scheme to obtain resolution on the order of 0.1 mm. With several modulation frequencies, distances on the order of kilometers can be measured. A fine measurement system has been developed which will work either in conjunction with the coarse system or independently. It uses a multi-state, two-color CO_2 laser which can be used to produce unambiguous measurements from 20 cm down to 0.01 μm resolution over distances to 100 m. A summary of the distance measuring capabilities is illustrated in Table 1.

Vibration measurements have been made using both Doppler frequency detection and a beat frequency phase measurement system with capabilities of measuring displacements less than a 0.1 μm at vibration frequencies from essentially DC to several kHz.

A feasibility demonstration of the coarse system capability was made under Contract No. 955130 for the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautics and Space Administration under Contract NAS7-100.

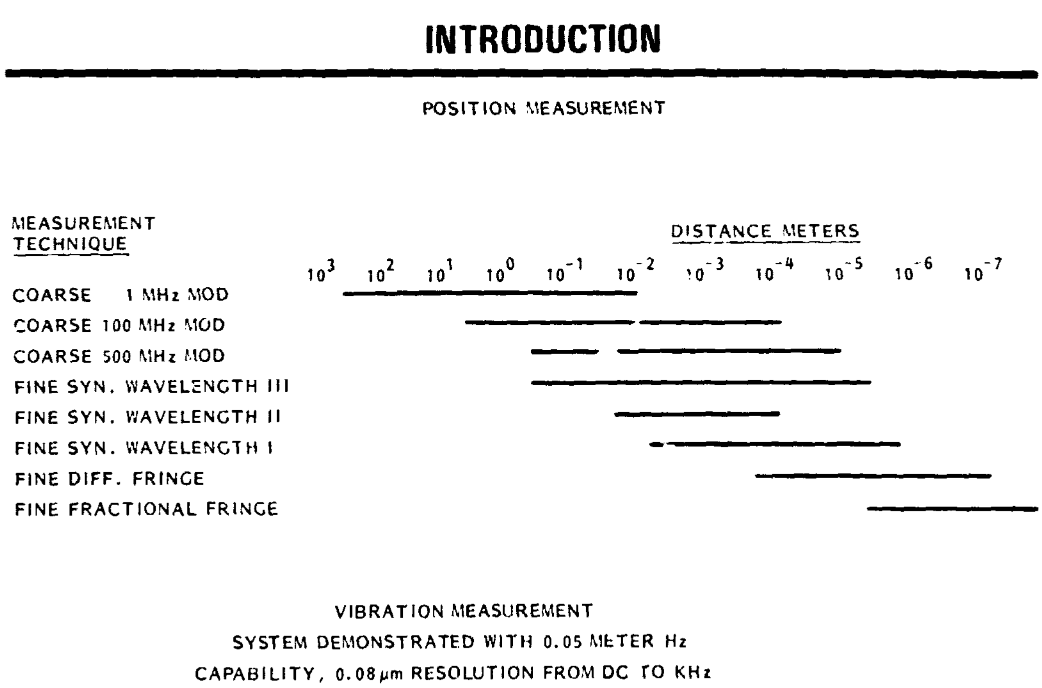


Table 1

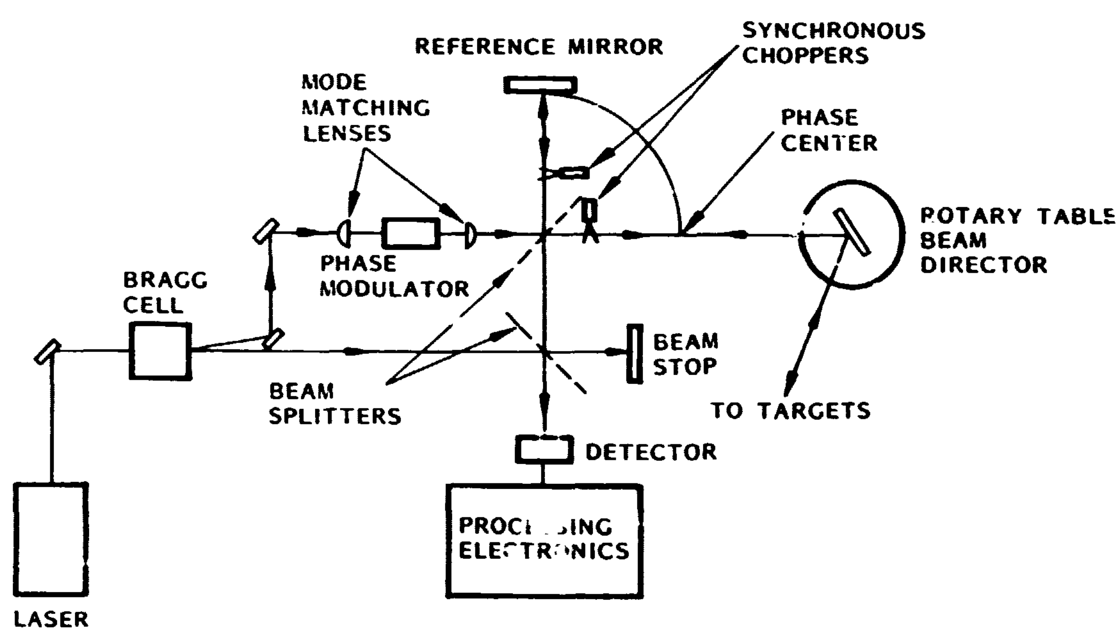
COARSE MEASUREMENT OPTICAL LAYOUT

The coarse system measures distance by accurately measuring phase of a modulated laser beam. Distance to a reference point is compared with the distance to the target. This method eliminates, through common moding, any drifts prior to the output beam splitter. Actual implementation of both CO_2 and HeNe systems has been accomplished. The following discussion applies to both systems.

An optical layout is illustrated. The beam from the laser is both spatially and frequency shifted by the Bragg cell. The unshifted portion of the beam is used as the local oscillator for the heterodyne receiver. The shifted beam is directed through the phase modulator with mode matching lenses. This modulated beam is split, and one sent to the reference mirror and the other to the target. Two choppers, 180° out of phase, sample the beams alternately for signal processing. For the demonstration, a mirror on a rotary table was used to direct the beam to the targets. Both the reference beam and target beam are returned to combine with the local oscillator beam to be received by the detector.

COARSE MEASUREMENTS – I

OPTICAL LAYOUT

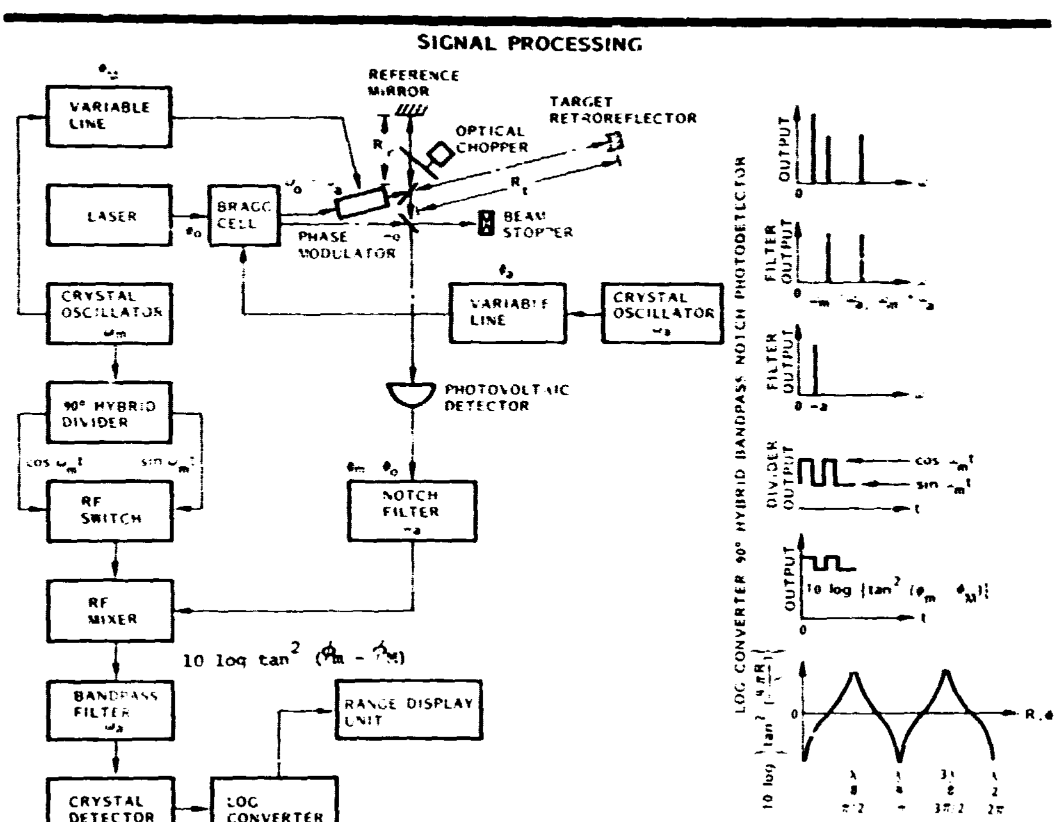


COARSE MEASUREMENT SIGNAL PROCESSING

The processing electronics consist of the system described below, as well as a micro-processor for converting the signals to a digital range output. LMSC has breadboarded the signal processing scheme described and demonstrated its performance.

The processing flow is shown in the figure. Beginning in the upper left-hand corner, FM modulation frequencies of 1.0 or 100 MHz are selectable by the RF switch. The selected RF power is divided and the first fraction passes successively through an adjustable (phase shifting) transmission line, a power amplifier, and a phase modulator for the working beam. The other fraction of the RF power passes to the 90^{o} hybrid divider where about one-half the power is phase shifted and two outputs corresponding to sine and cosine functions are provided. These outputs, each with a phase and amplitude trimmer, go to the inputs of a pair of SPST RF switches. The switch output provides the following RF mixer with sine and cosine inputs on alternate half cycles. The crystal detector, amplifier, and logarithmic voltmeter provide the output shown.

COARSE MEASUREMENT – II



The range, R, can be solved explicitly in a simple, straightforward manner as a function of the signal phase ϕ. The target range relative to the reference mirror can be calculated by subtracting two consecutive range measurements, one to the target and another to the reference mirror. The range resolution is

$$(\Delta R_m)_{min} = \frac{\lambda_m}{4}(\Delta\varphi_m)_{min} = \frac{\lambda_m^{\ 2}}{\pi A\sqrt{\left(\frac{S}{N}\right)}}$$

where λ_m = modulation wavelength

A = π x (modulation depth)

(S/N) = signal-to-noise ratio

$$\approx \frac{2\left(\frac{\eta q}{h\nu}\right)^2 P_\ell P_s}{B\left(\frac{2q^2}{h\nu}P_\ell + \frac{4kT_A}{R_L}\right)}$$

where

η = detector quantum efficiency

q = electron charge

$h\nu$ = photon energy

P_ℓ = optical local oscillator power

P_s = optical signal power

B = electronic bandwidth

k = Boltzman's Constant

T_A = equivalent temp. of amp.

R_L = resistance of load resistor

The range of resolution of a HeNe system is found to be comparable with that for a CO_2 system for the typical parameters listed in the table.

COARSE MEASUREMENT – III

HeNe – CO_2 COMPARISON

$$(\Delta R_m)_{min} = \frac{\lambda_m}{4}(\Delta\varphi_m)_{min} = \frac{\lambda_m^{\ 2}}{\pi A\sqrt{\left(\frac{S}{N}\right)}}$$

WHERE λ_m = MODULATION WAVELENGTH

A = π x (MODULATION DEPTH)

(S/N) = SIGNAL TO NOISE RATIO

$$\frac{(\Delta R_m)_{CO_2}}{(\Delta R_m)_{HeNe}} = \frac{160\ \mu m}{104\ \mu m} = 1.54$$

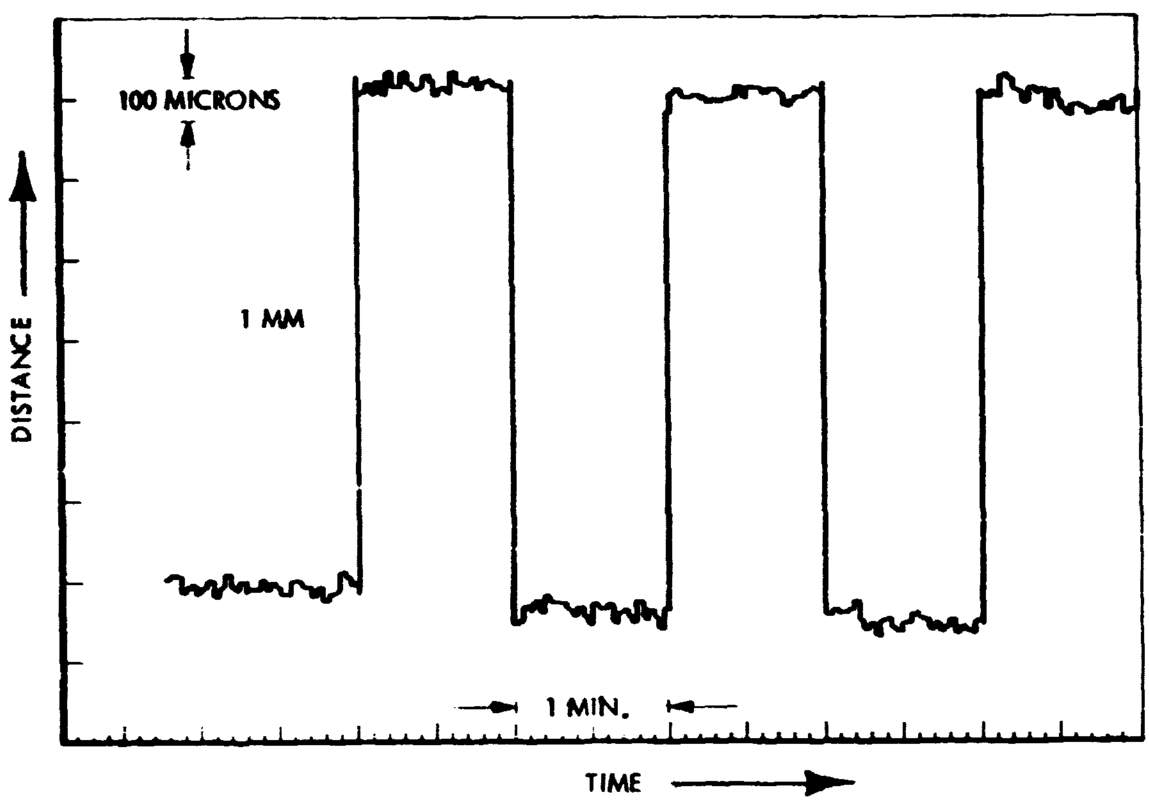
PARAMETERS FOR RANGE RESOLUTION CALCULATION

PARAMETERS		HeNe SYSTEM	CO_2 SYSTEM
λ_m	METER	3	
MODULATION DEPTH		0.2	0.02
η		0.8	0.5
q	COUL	1.6×10^{-19}	
$h\nu$	JOUL	3.13×10^{-19}	1.87×10^{-2}
P_ℓ	WATT	10^{-3}	
P_s	WATT	10^{-6}	
B	H_z	10^3	
k	JOUL/K	1.38×10^{-23}	
T_A	K	596°	
R_L	OHM	50	

COARSE SYSTEM RESOLUTION DATA

The coarse system range resolution data is shown for a 100 MHz CO_2 system. The target was translated back and forth in 1 mm steps, with the data averaged over 1 sec per reading.

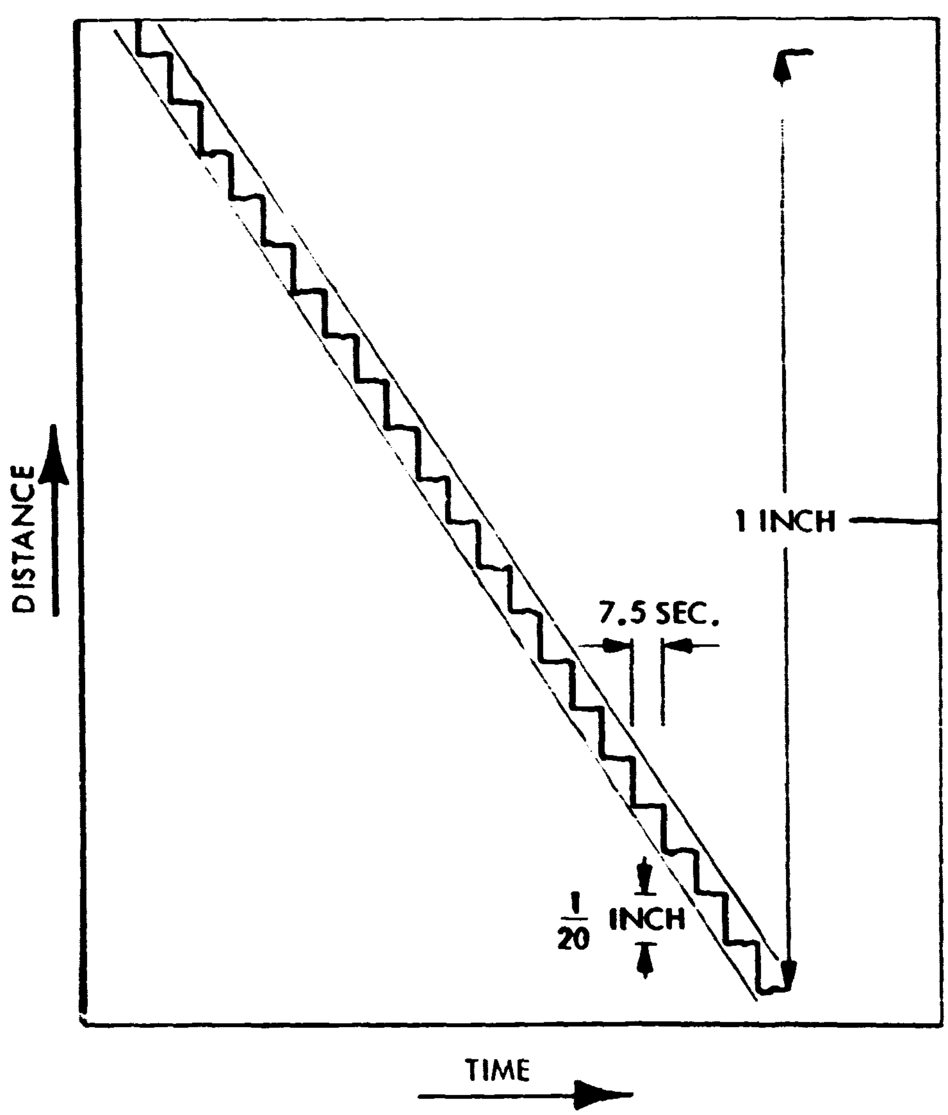
OPS RANGE RESOLUTION DATA



COARSE SYSTEM LINEARITY DATA

The linearity of the system is illustrated by the accompanying data. 1/20-inch steps were input and held for 7.5 sec over a total displacement of 1 inch.

OPS RANGE MEASUREMENT LINEARITY DATA



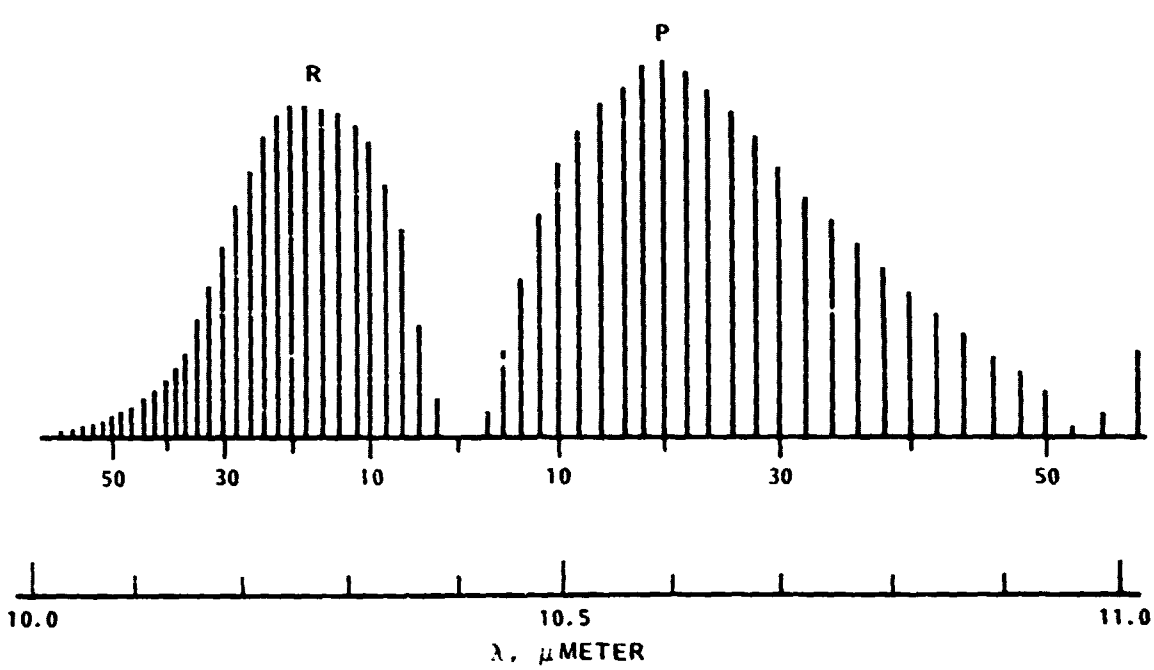
TWO-COLOR LASER OPERATION

The heart of the fine measurement system is the switchable two-color CO_2 laser. Gain occurs in the CO_2 gas mixture in many distinct lines corresponding to a given vibrational transition frequency. These lines, corresponding to R and P branches and numbered in each, are illustrated.

By controlling the cavity length, the line of operation can be established. If the length is such that an R frequency and P frequency have the same gain, they will operate simultaneously. This can be accomplished by separation of the signals (spectrally) and servoing a piezo-electric driven mirror to the proper cavity length. Thus, two-color operation is achieved. This can be refined further by selecting a specific R line and P line within the branches for laser operation. LMSC has developed a laser which can be switched through four pairs of lines.

FINE MEASUREMENTS – I

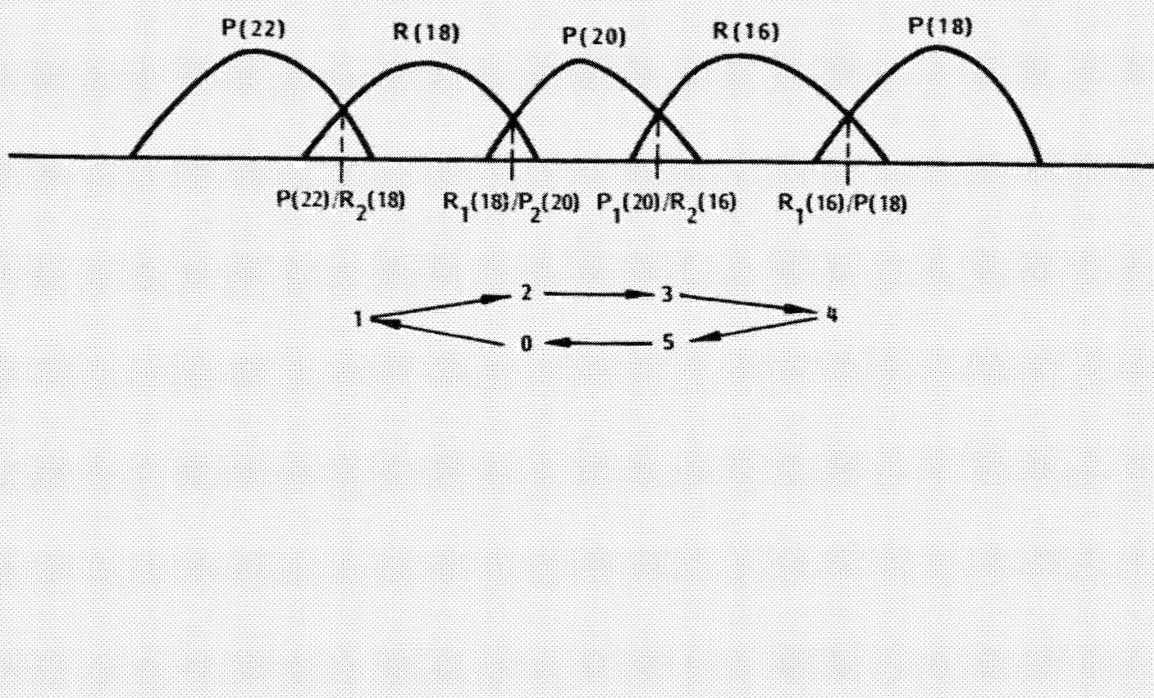
CO_2 GAIN CURVE 10.4 μM BAND



FOUR STATE SWITCHING

The four state switching sequence is illustrated. Starting at 0, the laser switches to positions 1 through 5 and back to 0. Each state is held for 70 msec by balancing the power between the two lines involved. The entire sequence takes about 280 msec.

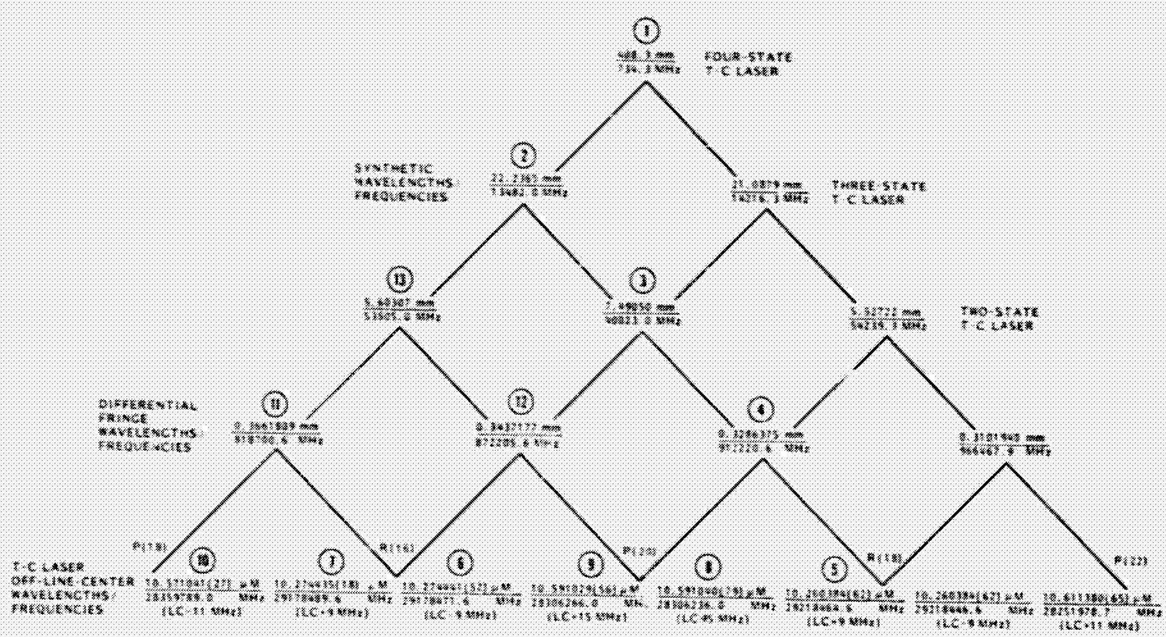
SWITCHING SEQUENCE SCHEMATIC OF FOUR-STATE T-C LASER



FINE SYSTEM WAVELENGTH HIERARCHY

By obtaining the frequency difference between pairs of lines, longer wavelengths can be produced. By looking at the difference between a pair of differential fringes, still longer wavelengths occur. In the figure, a hierarchy of wavelengths is established which can be obtained from the LMSC laser. The differential fringes are those obtained from a single two-color state. The synthetic wavelengths only exist in the comparison of one state to another. From this, it can be seen that an ambiguity of 40 cm can be obtained in total path length (20 cm in measuring distance). Ambiguities up to 15 m can be obtained by taking the difference of adjacent line center frequencies.

FOUR-STATE T-C LASER FREQUENCY/WAVELENGTH HIERARCHY PYRAMID



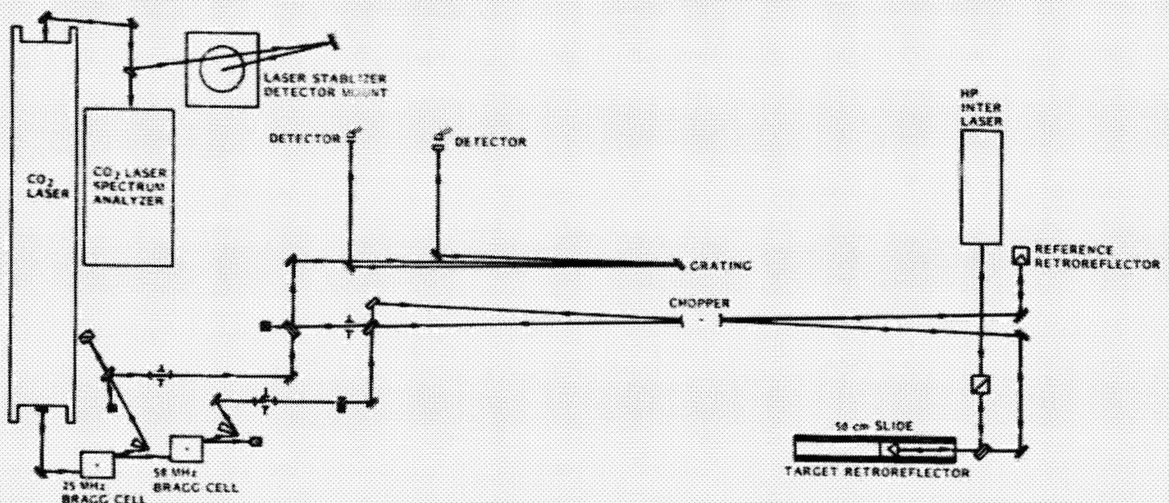
THE ABOVE DATA ARE BASED ON THE FOLLOWING:

- CO_2 TRANSITION LINE-CENTER FREQUENCIES
  - R(16) 29,178,480.6 MHz
  - R(18) 29,218,455.6 MHz
  - P(18) 28,359,800.0 MHz
  - P(20) 28,306,251.0 MHz
  - P(22) 28,251,967.7 MHz
- C = 299,792.5(00) KM/SEC.

FINE SYSTEM BREADBOARD LAYOUT

This figure illustrates the setup used to make comparitive measurements with an HP Interferometer. The LMSC sensor is chopped so as to alternately look at the reference and target retroreflectors. The HP tracks the target position and the output is compared to that of the LMSC sensor. The Bragg cells frequency shift the beam for heterodyning. The grating is used to separate the two colors for detection.

OPTICAL POSITION SENSOR BREADBOARD LAYOUT

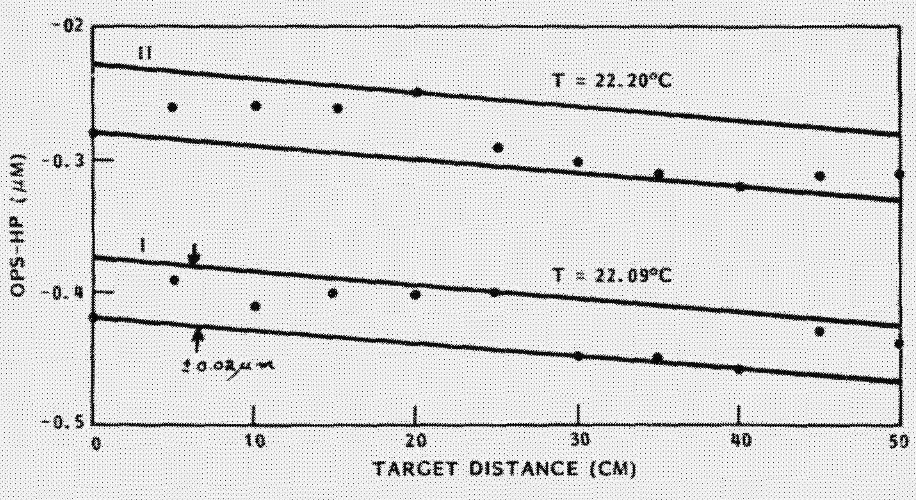


FINE SYSTEM ACCURACY DATA

Recent OPS-HP comparison measurements have been made using the previously shown breadboard wherein the OPS and HP beams were co-located as much as possible. Results achieved with this configuration show that the OPS-HP differential distance measurements vary nearly linearly with range, and that the statistical variation from linearity can be held to within $\pm 0.025\,\mu m$ over a 0-50 cm target excursion provided the temperature in the vicinity of the OPS "interferometer" is held constant to within approximately $\pm 0.01°C$.

This Figure presents typical data. Perfect agreement between OPS and HP would yield measurement data all in a straight line with zero slope. The measurements shown in the Figure, however, show a good linear relationship between OPS and HP, but an apparent wavelength discrepancy indicated for the most part by the linear bias of $+3.82\,\mu m/m$ (some 4 parts in 10^6). The "linear bias" represents an approximate straight line best fit to the OPS-HP differential measurement data; this linear portion of the measurement is removed in the computer and the residuals plotted using an expanded scale to more clearly reveal statistical variations.

DIFFERENTIAL DISTANCE COMPARISON MEASUREMENTS (OPS-HP)



ATMOSPHERIC CORRECTION: -265.57 μm/m

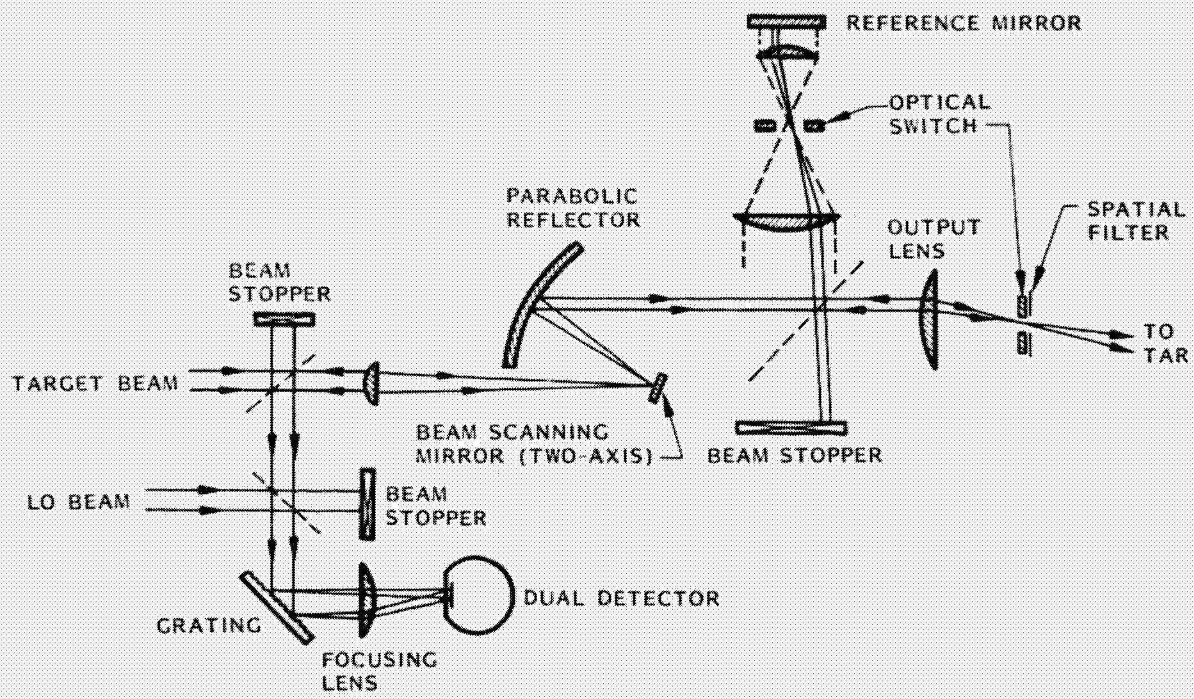
LINEAR BIAS: + 3.82 μm/m

FINE SYSTEM BEAM POINTING

A beam directing scheme needed to be devised which would not affect the path length. That scheme is also shown in the Figure where all errors occurring behind the output beam splitter are in a common mode in the reference and target measurements. It will require calibration of all measurement positions to account for optical differences but no scanner induced errors should occur.

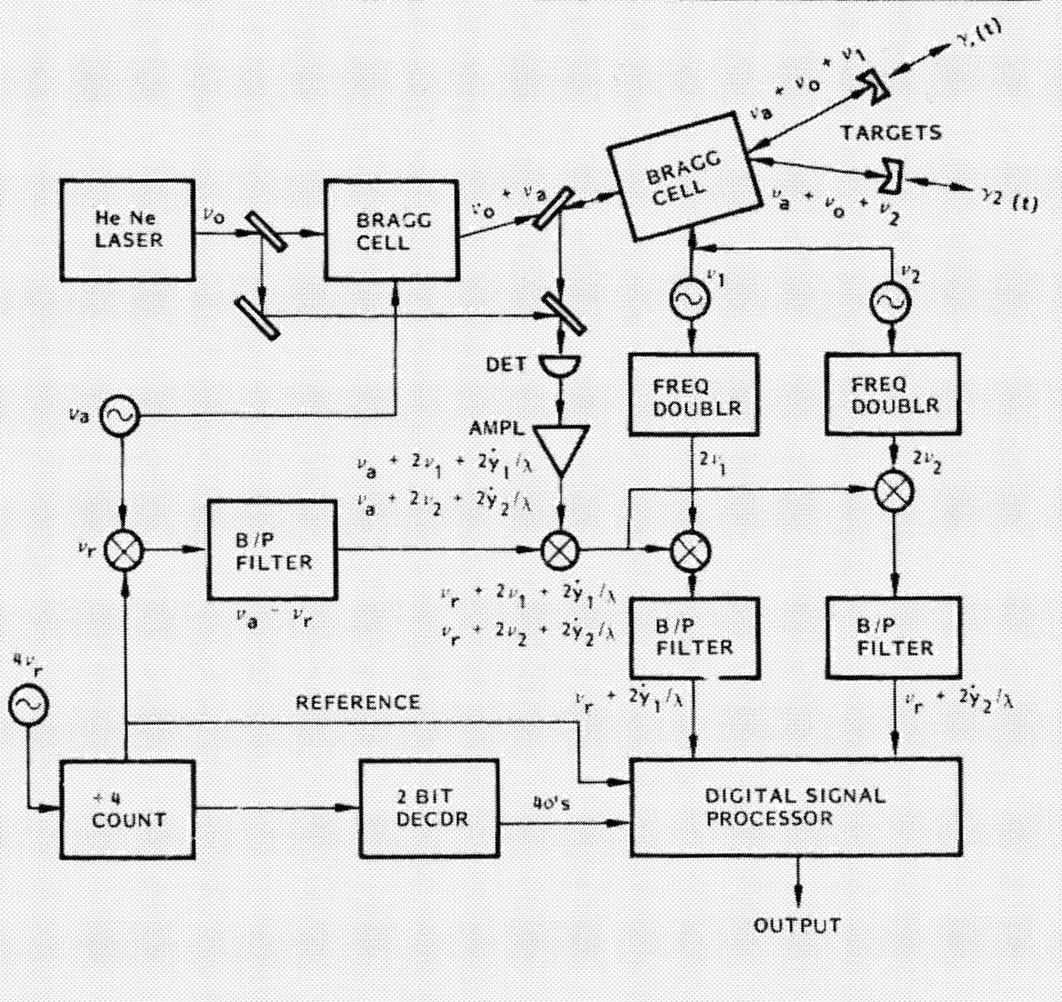
FINE MEASUREMENT – IV

BEAM POINTING SYSTEM



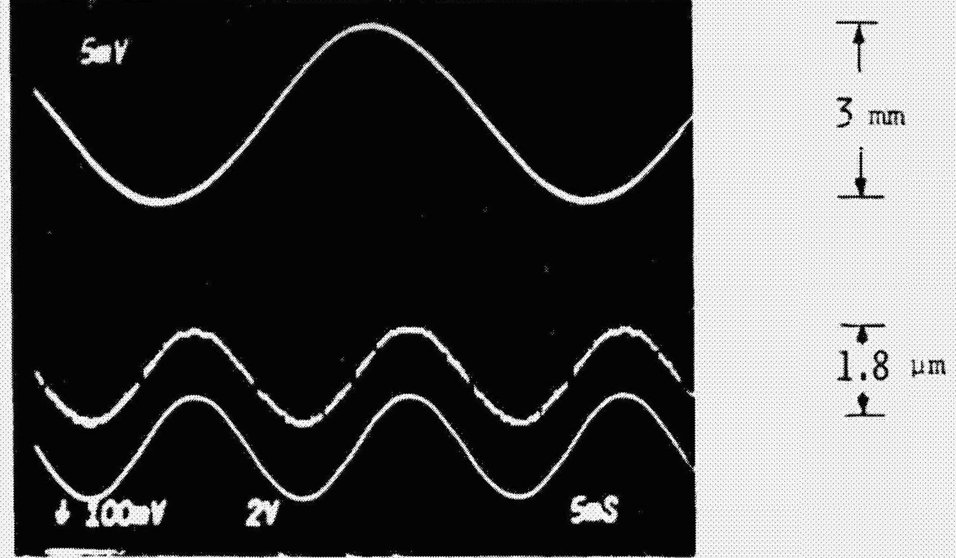
A HeNe laser Vibration Sensor has been demonstrated which features an analog and digital ouput for computational convenience, and which complements conventional vibration sensors by sensing vibratory events at low frequencies - from DC to beyond 50 Hz. Vibration amplitude resolution of the sensor is 0.08 μm, maximum amplitude and frequency product is 0.05 MHz for a 2 MHz electronic bandwidth. For example, the maximum measurable vibration amplitude for a 25 Hz vibration is 2 mm. The time delay of the sensor output from the actual vibration is less than 1 μsec which is essentially real time for measuring the dynamics of structures and vibration sensing for the dynamic damping of structures (active control). By electronically splitting the laser beam using a Bragg cell, it is possible to simultaneously sample and, hence, monitor a large number of points to which retroreflectors have been affixed. Although the laboratory Vibration Sensor employed but two channels, it exhibited the basis for continuously sensing more than 50 independent vibrating targets.

VIBRATION SENSOR — I



VIBRATION SENSOR DATA

The oscilloscope trace of the displacement of two vibratory targets is shown. In the Figure, the upper trace is the sensor output for channel 1 target vibrating at 30 Hz and an amplitude of 1.5 mm. The middle trace is the sensor output for channel 2 target which measures a 60 Hz vibration at an amplitude of 0.9 μm. It is noticeable that the "stair-like" waveform is a result of digital signal processing. Each step of the stair represents 0.08 μm displacement of target which is the resolution of the present system. The lower trace represents the driving signal to the PZT for channel 2 target. Comparing the output of the Vibration Sensor with the driving signal of the target mirror indicates a time delay of about 1 μsec between the sensor output and the actual vibration, of which, about 500 nsec is contributed by the digital circuitry (between the falling edges of input sampling clock $\emptyset_1$ and output sampling clock $\emptyset_5$), the rest of it is due to the settling time of D/A converter.



VIBRATION SENSOR OUTPUT FOR TWO VIBRATORY TARGETS (EXHIBITION OF AMPLITUDE RANGE AND SENSITIVITY OF SENSOR)

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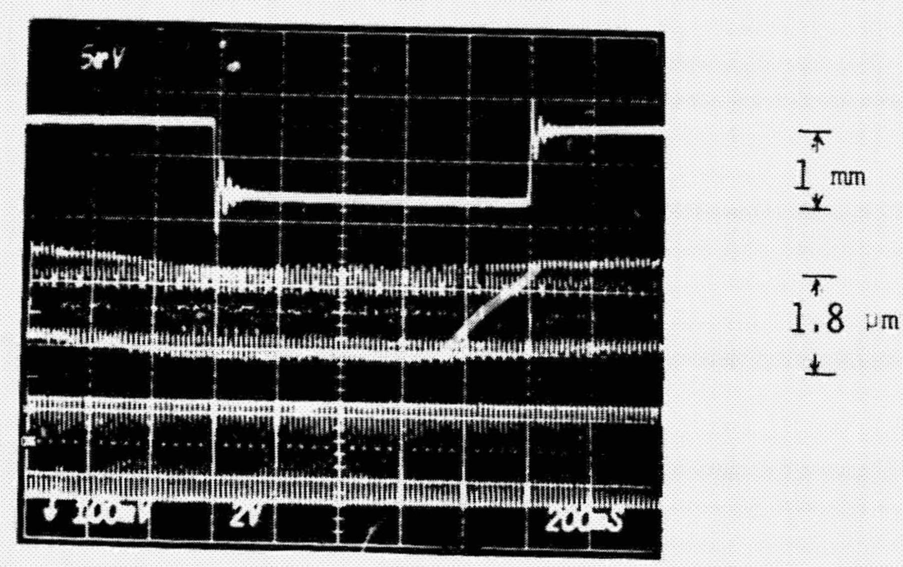
VIBRATION SENSOR DC RESPONSE

The DC response of the sensor is shown in the upper trace of this Figure. The only difference between this and the previous experiment is the driving voltage applied to the shaker for channel 1 target. In this experiment, a 0.5 Hz square wave is applied to the shaker. The sensor measures the steady state DC displacement (~1 mm) as well as the transient behavior of the shaker.



VIBRATION SENSOR OUTPUT FOR TWO VIBRATORY TARGETS

(EXHIBITION OF AC AND DC RESPONSE OF SENSOR)

CONCLUSIONS

Based on the analyses and the breadboard demonstrations performed at LMSC, we have made the following conclusions:

- It is possible to measure distance with HeNe absolutely from km down to 0.1 mm.
- It is possible to measure distance with CO_2 from km down to 0.01 μm.
- Rates on the above measurements can be made from rates of 1 per sec to 100 per sec.
- It is possible to measure vibrations from DC to kHz with up to 50 channels per detector/laser.

The primary concern in the application of the above sensors is one of beam direction and integration into the structural system being controlled. This problem is best approached for each system configuration.