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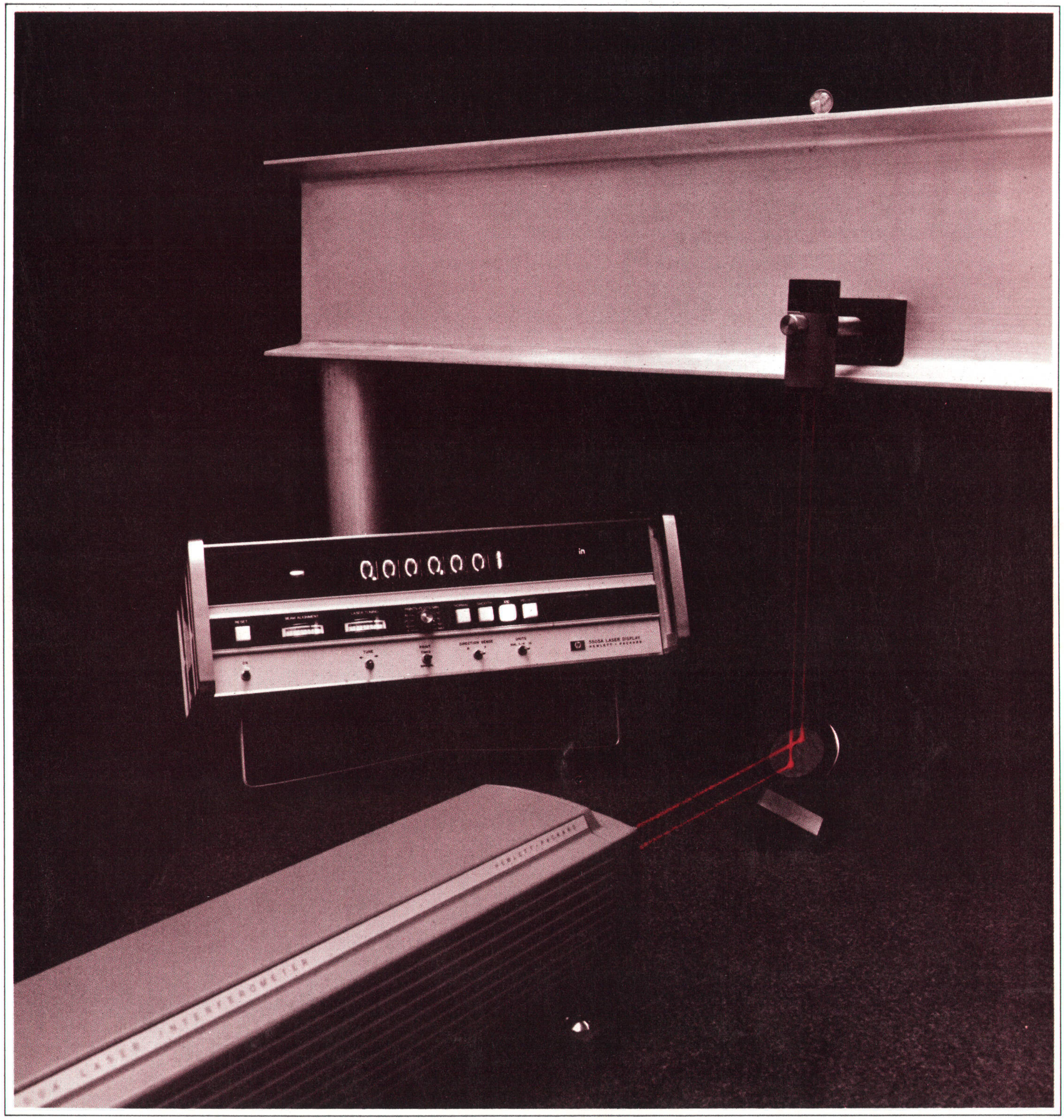


AUGUST 1970

A Two-Hundred-Foot Yardstick with Graduations Every Microinch

This new and innovative laser interferometer is ready to measure distance with no warmup at all. From its specially designed two-frequency laser and heterodyning techniques it derives increased sensitivity and resistance to air turbulence. With its internal computer it can smooth jittery readings, calculate velocity, and improve resolution.

By John N. Dukes and Gary B. Gordon

A LASER BEAM makes an eminently practical working standard for measuring length. With its high degree of coherence, it is usable over distances of hundreds of feet. Its short wavelength permits resolution into the microinch range. Its wavelength can be determined to a high degree of accuracy—parts in 10^7 or better. It is locked to an atomic transition in neon and to the velocity of light, and does not require periodic recalibrations. On this yardstick, the graduations are laid down by nature herself.

The new HP Model 5525A Interferometer is a portable distance-measuring standard which takes advantage of these desirable laser attributes, and incorporates as well a number of refinements which give it significantly better performance, reliability, and ease of use than other interferometers. It measures distances from zero to more than 200 feet. It has one microinch resolution (0.4 μin or 10^{-8} m when measuring in metric units) and is accurate within five parts in 10^7. There is no need to wait an hour or more after turn-on for it to warm up; it meets its accuracy specification immediately and maintains itself in tune automatically. It has electronic averaging to make readings rock-steady even in the presence of minute vibrations, and it has unusual immunity to air turbulence, the most common cause of poor interferometer performance.

Fits In a Suitcase

The interferometer has three components (see Fig. 1): a laser head that generates a low-power laser beam, a reflector that returns the beam to the laser head, and a control box that computes and displays the readings. The entire system is so compact that it can easily be carried from place to place in a suitcase. It weighs only 44 pounds.

In practice, either the laser head or the reflector is mounted on the device whose movement is to be measured, and the other unit is mounted at a fixed point. The control box can be placed anywhere allowed by the single 15-foot cable connecting the box to the laser head.

The reflector is a glass trihedral prism, or 'cube corner,' similar to the ones recently placed on the moon. Distance is measured by electronically counting wavelengths of light. Distance *change* is measured, rather than the absolute distance between the laser head and the reflector. Thus any point may be defined as a zero reference.

Cover: *Model 5525A Laser Interferometer has one-microinch resolution (0.4 microinch when displaying in metric units), but what does this mean? We decided to find out, and this cover is the result. That's a four-foot-long aluminum beam, and the penny deflects the center of it about a microinch.*

In this Issue:

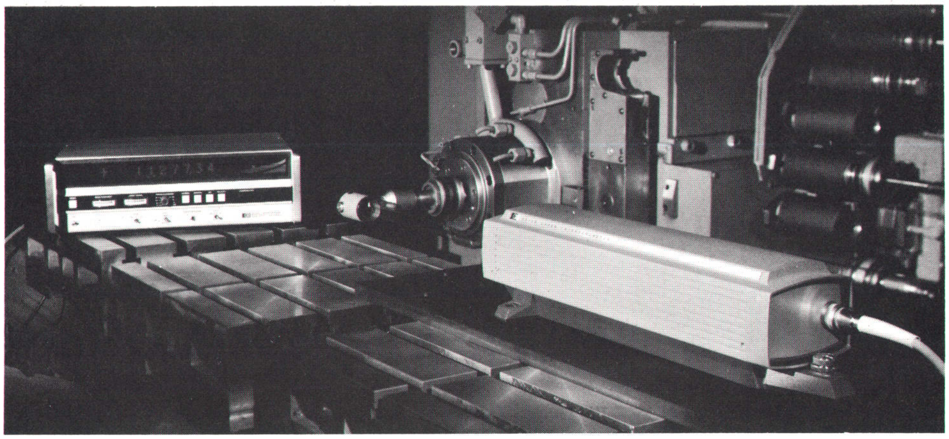


Fig. 1. *Model 5525A Laser Interferometer is a rugged, easy-to-use distance-measuring system with a range of 200 feet, accuracy better than 5 parts in 10⁷, and usable resolution better than one microinch. Its new two-frequency laser warms up instantly, runs cool, and doesn't mind air turbulence, the most common cause of poor interferometer performance.*

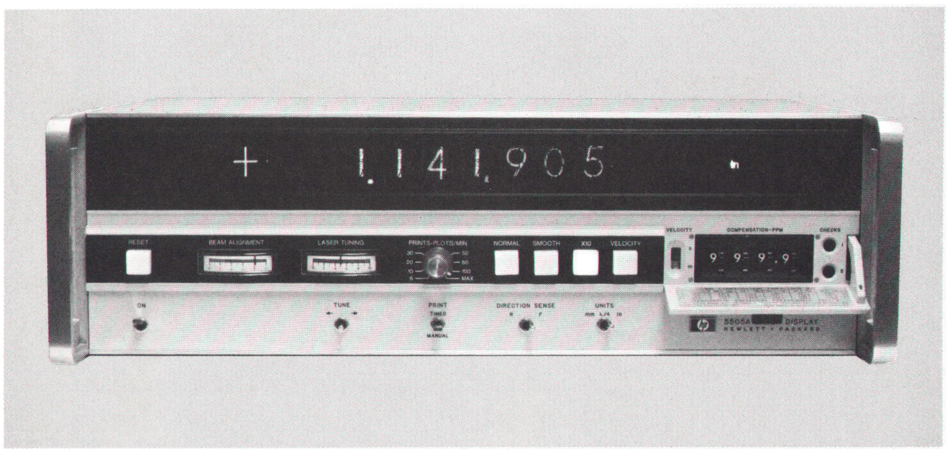


Fig. 2. *Model 5525A Interferometer has 10 microinch resolution in NORMAL and SMOOTH modes, one microinch in X 10 mode. In the SMOOTH mode, successive readings are averaged to eliminate vibration-induced jitter in the display. The system can also display the moving reflector's velocity, up to 720 in/min. Behind the door at right are thumbswitches for setting in velocity-of-light corrections.*

To convert from wavelengths of light to useful units of inches or millimeters the interferometer performs several operations. The wavelength, about 25 microinches, is first divided electronically to finer than one microinch. The result is then multiplied digitally by the wavelength of the laser light in either English or metric units, corrected for slight variations in the velocity of light due to the temperature, pressure, and humidity of air, and finally displayed to 9 digits as the distance traversed.

Two Frequencies Fight Turbulence

The interferometer derives its immunity to air turbulence from a new two-frequency system, described in detail later in this article. Turbulence has always been a serious problem for laser interferometers. The same heat waves that cause a distant image on the horizon to flutter can also affect the laser beam. The effect is equivalent to an intensity variation. Similar intensity variations are produced by absorption and dispersion from atmospheric contaminants such as smoke or oil mist, and by dirt films on the optical surfaces. A measure of an interferometer's ability to operate under these adverse conditions is the maximum loss of returned beam it can tolerate.

Where most interferometers are comfortable with 50% loss of signal, the two-frequency interferometer tolerates more than 95%. This additional margin of safety also frees the two-frequency interferometer from periodic electrical adjustments. There are no adjustments for beam intensity or triggering threshold. Furthermore, the interferometer tolerates signal variations produced when the reflector is rotated, so it can make measurements such as dynamic growth of a lathe spindle resulting from bearing self-heating.

Special Laser Designed

The heart of the interferometer is a unique single-mode helium-neon gas laser specifically designed for this application. Its output is a continuous red beam at 632.8nm (6328Å). Conventional laboratory lasers are stabilized by placing them in an oven, but for a portable distance-measuring device this presents two drawbacks. First, the time required for the oven to stabilize can approach an hour, and second, the heat of the oven can cause the object being measured to expand, thereby invalidating the results. In the new laser, the laser cavity is stabilized by using an internal zero-coefficient-of-expansion structure, combined with a servo loop for automatic tuning. The results are zero warmup time and a cool-running optical head. Also, since the tuning system doesn't have to dither the laser frequency to find line center, the display is steadier than that of other interferometers. This laser is the subject of the article beginning on page 14. Other design goals contributing to its unusual configuration were long lifetime and ruggedness.

Modes of Operation

The new interferometer has several modes of operation. In the normal mode display is nearly instantaneous, to a resolution of 10 millionths of an inch. In this region one becomes suddenly aware of how flexible even massive structures can be. Granite surface plates and large machines may be deformed by mild pressures, and vibrations produced by nearby motors produce small rapid dimensional fluctuations. When present these are seen as superimposed digits in the rightmost display tube, since the vibrations are faster than the eye can resolve.

Frequently one would like to see through such vibrations to observe other deflections, such as machine deflection under loading by the workpiece. The 'smoothing' mode of operation effectively accomplishes this. In this mode, a sequence of measured values is low-pass-filtered digitally so the display shows the average position rather than the instantaneous position. Thus the reading becomes rock-steady.

The normal and smoothed modes display distance with a resolution of 10 millionths of an inch, or about one five hundredth the diameter of a human hair. Fine as this is, there are applications in metrology, photogrammetry, and integrated-circuit mask-making for which more resolution is desirable. In the ×10 mode resolution is electronically extended by interpolating between fringes. Resultant resolution is one microinch in English units, or 10^{-8} m in metric units. 10^{-8} m (0.4 microinches) is about 25 times the atomic spacing in a crystal lattice.

An internal time reference is included for digital velocity or feed rate measurements up to 1 foot/second or 720 inches/minute. These are derived by subtracting subsequent distance measurements at precisely known intervals.

Velocity of Light Corrections

Behind a front-panel door (Fig. 2) is a vernier for making, in effect, fine and calibrated adjustments in the length of the standard. An example of its use is in calibrating a machine at an elevated temperature, say 78°, and correcting the results back to 68°. If the machine is cast iron and has a coefficient of expansion of 6.5 ppm/°F, then it will be 65 ppm too large at 78°F. Correction is effected by subtracting 65.0 from the thumbwheel switch reading.

Another use for these switches is to make slight corrections for variations in the velocity of light for very precise measurements. A simple table converts readings of barometric pressure and air temperature into the proper number to enter on the switches.

Within a few months an accessory will be available which will automatically compute the velocity-of-light correction. It will have sensors to measure air pressure, air temperature, and machine temperature. There are good arguments for both approaches; manual entry of the correction factor has the advantage of being both economical and conducive to good measurement technique, while automatic compensation saves a few operator steps but requires periodic recertification to maintain accuracy. Other accessories, which are available now, are a printer and a 90° beam-bender.

Human Engineering

Many man-hours went into the human engineering of the interferometer, and the result proves that a basic length-measuring instrument need not be complicated to be accurate. For example, the operations of starting the laser, tuning and locking it, and resetting the display are performed automatically when the power switch is turned on. Seldom-used controls such as electrical self-checks are placed behind a front panel door. Only low voltages are carried on the cable to the interferometer, so no shock hazards are present should a chip cut into the cable. For easier readability, insignificant leading zeros on the display are automatically blanked. Front-panel range changes or units changes (e.g., metric to English) do not destroy the distance information, and when the instrument is switched out of velocity or feed-rate mode, the distance reading is still valid.

The cube-corner reflector was designed for unusual versatility in mounting and ease of alignment (Fig. 3). Holes allow 90° rotation, and turning a single knurled ring clamps all axes. The base may be interchanged with standard magnetically clamped bases. The column and a rear shoulder on the housing are both ⅝ inch in diameter, for easy retention in collets or chucks. There is also a rear thread for mounting the cube-corner perpendicular to flat surfaces.

How Interferometers Work

When Apollo 11 landed man on the moon for the first time, a corner reflector was set up as part of an experiment to measure the distance to the moon very precisely. Laser pulses were bounced off the reflector, and the time of travel of the *envelope* of each pulse was a measure of the distance. A radar measures distance in the same way, but at a lower carrier frequency.

Interferometers measure distances in a different way, that is, by counting wavelengths of the *carrier* signal, rather than by measuring the travel time of the envelope of the carrier. All modern interferometers are based on techniques pioneered by A. A. Michelson in the 1890's (Fig. 4).

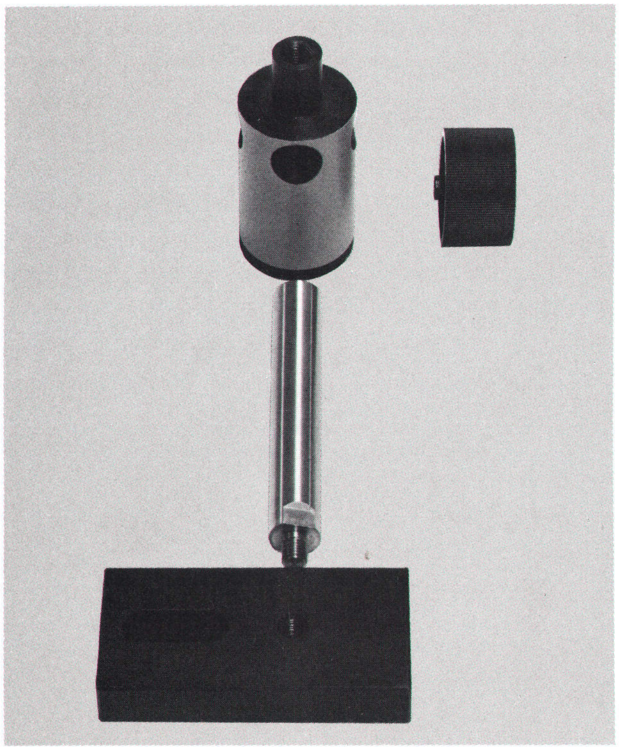


Fig. 3. *Reflector, or 'cube corner', is designed for easy mounting in a variety of ways, and for easy alignment. Turning a single knurled ring clamps all axes.*

Michelson used a half-silvered mirror to split the beam from a light source into two beams, each of which was reflected from a mirror and again recombined at the half silvered mirror. With the mirrors exactly aligned and motionless the observer sees a constant intensity of light. But if one of the mirrors is moved very slowly the observer will see the beam repeatedly increasing and then decreasing in intensity as the light from the two paths adds and cancels. Each half wavelength of mirror travel means a total optical path change of one wavelength and one complete cycle of intensity change. If the wavelength of the light is known, then the travel of the mirror can be accurately determined. It's important to note that the distance out to the moving mirror may not be known; interferometers measure the *changes of position* of the mirrors with respect to each other.

To convert Michelson's apparatus into an electronic measuring instrument basically requires only a photocell to convert beam intensity into a varying electrical signal, and an electronic counter to tally the cycles of beam intensity. To make such a device practical, however, several other improvements are necessary.

First, because mirror alignment is extremely critical, modern interferometers use cube corners instead of mirrors. Cube corners reflect light parallel to its angle of incidence regardless of how accurately they are aligned with respect to the beam. Second, modern interferometers use lasers as light sources, for two reasons: if the interferometer is to be used over any significant distance the light must be pure, i.e., single wavelength; if the interferometer is to be accurate, the wavelength must be exactly known. The laser satisfies these criteria beautifully.

A third improvement is direction-sensing electronics. A single photocell isn't sufficient to sense which way the reflector is being moved. The method used by most interferometers to sense direction is to split one of the optical beams into two portions, delay one portion in phase by 90°, and then, after recombination, detect each portion of the beam using a separate photocell. This technique gives two signals which vary sinusoidally in intensity as the reflector is moved, and they differ in phase of brightness by 90°. These two signals, after dc amplification, can be used to drive a reversible counter, and the phase separation is sufficient to inform the counter of the direction sense of the motion.

Although all commercial interferometers to date have been built this way, there is a fundamental problem with this conventional system. Fig. 5(a) illustrates the output of one of the photocells as one of the reflectors is moving. Notice that the intensity variations are centered around the triggering levels of the counter. But if the intensity of either light beam or the intensity of the source should change, the variations in intensity may not cross the triggering levels. Fig. 5(b) illustrates this condition. Thus a change in intensity can stop operation until the trigger levels are readjusted. Such a change in intensity conventionally occurs as the laser ages; it always occurs when turbulence either deflects the beam slightly or warps the wavefront, and, while trigger levels can be adjusted

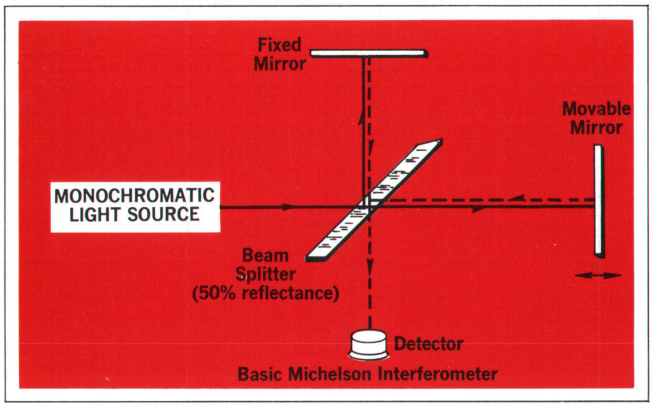


Fig. 4. *Laser interferometers are based on the Michelson interferometer of the 1890's. If one of the two mirrors moves, the observer sees the light repeatedly increasing and decreasing in intensity as light from the two paths alternately adds and cancels. Each cycle of intensity corresponds to a half-wavelength of mirror travel. If the wavelength of the light is known, intensity cycles can be counted and converted to distance traveled.*

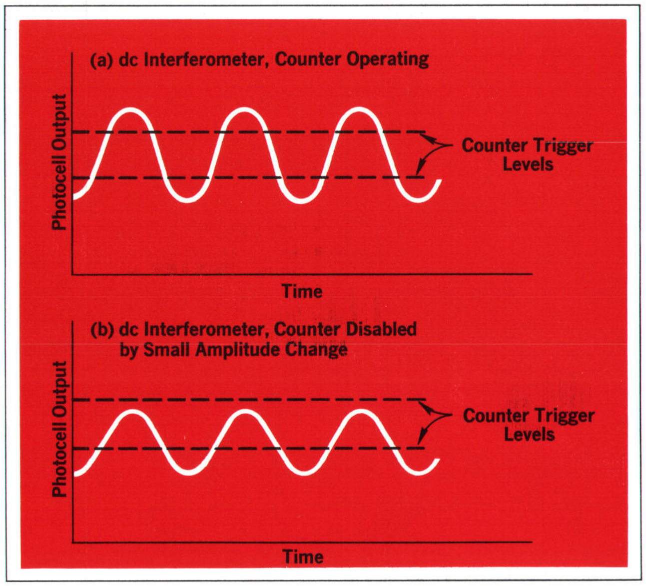


Fig. 5. *Most laser interferometers use dc systems in which intensity changes due to aging or air turbulence can interfere with triggering and cause improper counting. The new HP interferometer uses an ac system which doesn't have this problem.*

for long-term changes, no automatic trigger-level adjustments can follow the fast changes in intensity one usually finds in a shop atmosphere where the interferometer is often used.

Two Frequencies Are Better Than One

The new HP interferometer operates on a heterodyne principle and completely avoids this problem. While conventional interferometers mix two light beams of the same frequency, the HP interferometer uses a two-frequency laser and mixes light beams of two different frequencies. Fig. 6 is a diagram of the system.

The virtue of the two-frequency system is that the distance information is carried on ac waveforms, or carriers, rather than in dc form. Unlike dc amplifiers, ac amplifiers are not sensitive to changes in the dc levels of their inputs.

The ac signals representing distance change are generated in a manner exactly analogous to the intermediate frequency carriers in the everyday FM heterodyne radio receiver. The ac signal or 'intermediate frequency' is produced by mixing two slightly different optical frequencies, near 5×10^{14} Hz, differing by only parts in 10^9. If these had to be generated by different sources, the stability requirements would be almost prohibitive. But by a fortunate circumstance, a laser can be forced to oscillate on two frequencies simultaneously, simply by applying an axial magnetic field. The two frequencies that result are very close together, but the corresponding components of the laser beam have opposite circular polarizations and can therefore be separated by polarized filtering.

One of the two frequency components is used as the measuring beam and reflected from the cube corner. On return it is mixed with the second frequency, or 'local oscillator' in receiver language. The mixing produces the well-known fringe patterns of alternate light and dark bands caused by alternate constructive and destructive interference. The eye can't resolve these bands, however, since they flicker at a rate of several million per second. If the movable cube-corner reflector happens to be stationary, the rate will be exactly the difference between the laser's two frequencies, about 2.0 million fringes/second. Now if the reflector is moved, the returning beam's frequency will be Doppler-shifted up or down slightly, as with a passing train's whistle. A reflector velocity of one foot per second causes a Doppler shift of approximately 1 MHz. This fringe frequency change is monitored by a photodetector and converted to an electrical signal. A second photodetector monitors fringe frequency before the paths are separated, as a reference for the fringe rate corresponding to zero motion.

These two frequencies from the photodetectors are next counted in a form of reversible counter. One frequency produces up-counts, the other down. If there is no motion, the frequencies are equal, and no net count is accumulated. Motion, on the other hand, raises or lowers the Doppler frequency, producing net positive or negative cumulative counts corresponding to the distance traversed in wavelengths of light.

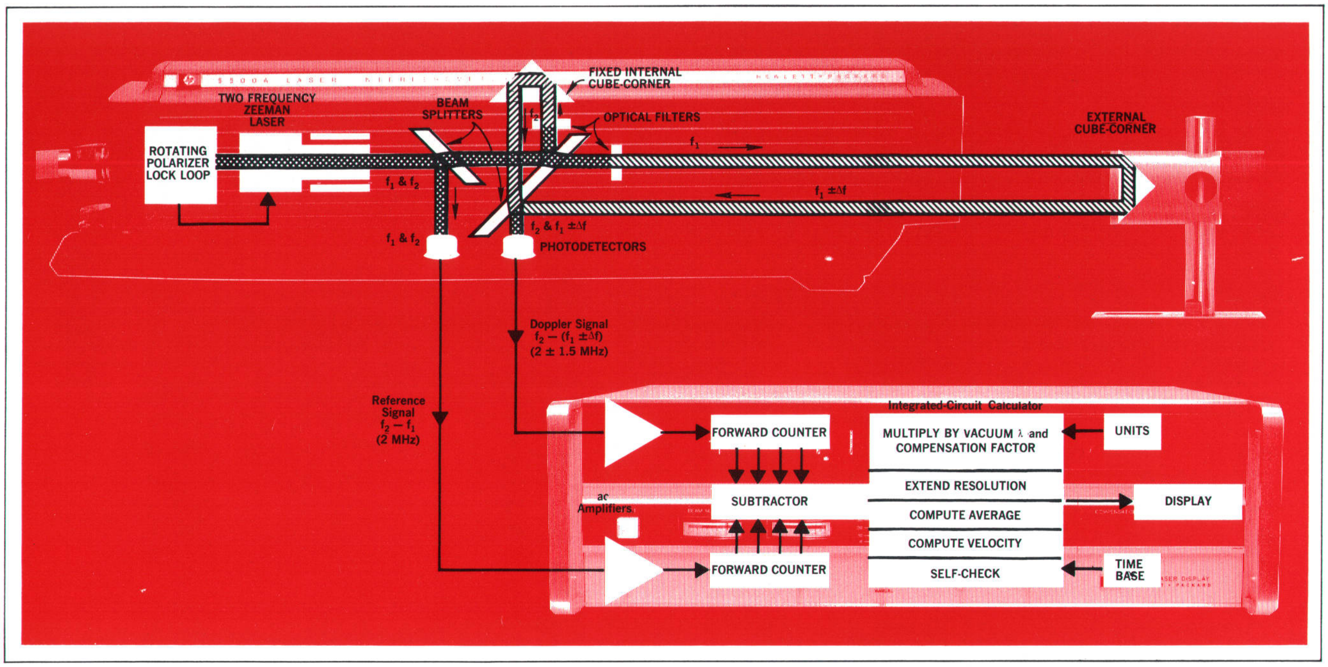


Fig. 6. *In the HP interferometer, two frequencies are generated by the laser and separated by optical filters of opposite circular polarizations. The beam of frequency f_1 is Doppler-shifted as it bounces off the moving reflector. The returned beam is optically mixed with the beam of frequency f_2 and the difference frequency is detected, amplified, counted, and converted to distance traveled.*

IC Calculator

A small integrated-circuit calculator converts these wavelengths to English or metric units of length. The low cost, small size, and high reliability of IC's make such a calculator feasible for this application. And as a bonus, having the flexible calculator present makes it economical to include other functions, such as smoothing, resolution extension, and velocity computation.

Smoothing is done by first storing the previous distance reading. Then when a new distance is computed, it is not displayed. Rather, the previous distance reading is changed slightly (0.1%) toward the new distance, and this result is displayed. Consequently the display is sluggish to rapid changes. This digital low-pass filtering is the logic designer's counterpart of the mechanical engineer's dashpots and the analog designer's RC filters. Resolution extension is achieved in much the same way, by random sampling and averaging. Velocity is computed by subtracting subsequent readings at tenth-second or thousandth-minute intervals.

Acknowledgments

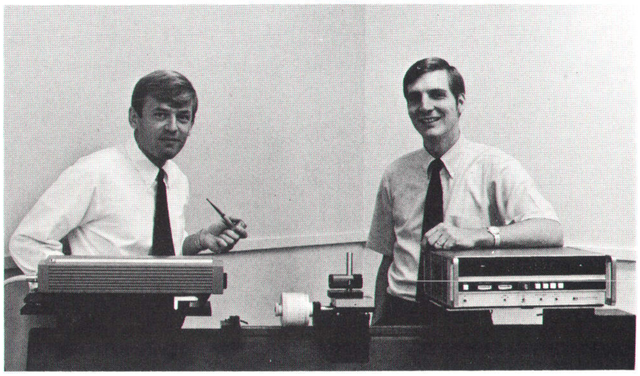
Several years ago when HP engineers were first experimenting with interferometry, they found that variations in optical intensity were causing miscounts and intermittent operation. Santa Clara Division manager Al Bagley, a fast man with an analogy, suggested heterodyne operation similar to that used in frequency-measuring instruments and radio receivers. Such a system, he felt, would allow the use of ac amplification and eliminate the need for critical (and changing) dc level adjustments.

The invention moved fast from that point. Len Cutler conceived several methods for furnishing two frequencies from one single-mode laser. Don Hammond proposed optical schematics. Joe Rando contributed ideas on all fronts.

A good invention needs good treatment to be a usable instrument. This was the job of the laser measurements section of the Santa Clara Division. Ken Wayne began the project as a mechanical engineer and emerged an optical designer. The structural, thermal, and magnetic design was coordinated by André Rudé with help from product designer Roy Ingham. Later in the project they were assisted by Jobst Brandt and Jim Marrocco. Bringing five years of interferometer experience, Dick Baldwin joined mid-course as optical engineer.

The attractive industrial styling is by Roger Lee. Jon Garman made numerous digital design contributions. Analog assistance was lent by John Corcoran and Lyle Hornback. Production engineer Carl Hanson smoothed the road to replication.

John N. Dukes



John Dukes has degrees from Oberlin College (BA) the Universities of North Dakota (BSEE) and California (MSEE), and Stanford University (EE). As engineering section manager, he supervised development of the new laser interferometer, along the way gathering three patents pending, one on a laser locking system, another on a laser power supply, and a third on an interferometer thermal compensation technique. John previously helped design two synthesizers and led a heterodyne-converter project. In his spare time he plants trees and plays the baritone saxophone, but not, he says, simultaneously.

Gary B. Gordon

Gary Gordon received his degree in electrical engineering from the University of California. Before becoming project leader on the laser interferometer, he did logic design on the HP Computing Counter and conceived the Logic Probe and Logic Clip, two handy gadgets for IC logic checkout. Gary has seven patents pending, three of which cover the interferometer's error plotting, smoothing, resolution extension, and counting techniques. He received his MSEE this year from Stanford University, which means that he'll now have less studying to do and more time for sailing and designing contemporary furniture.

SPECIFICATIONS

HP Model 5525A
Laser Interferometer

ACCURACY (exclusive of velocity of light, alignment and work piece temperature):
5 parts in 10^7 ± 1 count in least significant digit (± 2 counts in metric units).

RESOLUTION (least count):
NORMAL MODE: 0.00001 in or 0.0002 mm.
$\times$ 10 MODE: 0.000001 in or 0.00002 mm.

OPERATING RANGE: 200 ft, 60 meters, in typical machine shop environments.

MAXIMUM MEASURING VELOCITY: 720 in/min (1 ft/s), 0.3 m/s.

VELOCITY MEASUREMENT:
RANGE:
ENGLISH: 0 to 12 in/s, 0 to 720 in/min.
METRIC: 0 to 300 mm/s, 0 to 18,300 mm/min.
ACCURACY AND RESOLUTION:
ENGLISH: ± 0.0001 in/s, ± 0.01 in/min.
METRIC: ± 0.002 mm/s, ± 0.2 mm/min.

WARMUP TIME: None

LASER TUNING: Laser tuning is automatic.

DISPLAY: 9 digits with appropriate decimal point and comma, and + or − sign.
UNITS:
NORMAL, SMOOTH and $\times$ 10 MODES: in, mm, $\lambda/4$
VELOCITY MODE: in/s, in/min, mm/s or mm/min.
Display in all modes (Normal, Smooth, $\times$ 10, and Velocity) and all units available at any time during or after a measurement without loss of any information.
Nonsignificant leading zeros are blanked for readability.

RESET: Pushbutton reset to zero.

ERROR INDICATORS: Beam interrupt, overspeed.

TEST CIRCUITS:
Front-panel pushbutton-operated test circuits verify that all computing circuits are operating properly.

ALIGNMENT TO MEASURING AXIS:
Built-in three-point kinematic suspension and precision adjustment permits accurate alignment to measuring axis. Signal strength meter on front panel makes possible easy positioning of retroreflector for maximum optical signal.

INTERCHANGEABILITY:
Any HP interferometer head will operate with any HP display unit.

VELOCITY OF LIGHT COMPENSATION:
A combined factor for barometric pressure, temperature, and humidity is derived from a supplied table. The factor, directly in parts per million with 0.1 ppm resolution is manually entered via thumbwheel switches. The range of this factor is large enough to cover any possible set of environmental conditions.

MATERIAL THERMAL EXPANSION COMPENSATION:
Thermal expansion compensation in parts per million is manually entered via thumbwheel switches.

INPUTS:
Automatic velocity of light compensation or remote manual VOL compensation.
Auxiliary: Remote front panel controls, i.e., Reset, Manual Print, Normal, Smooth, $\times$ 10, Velocity, Tuning Error, Beam Interrupt Error.

OUTPUTS:
BCD output for printer, computer, Fourier analyzer, etc. Timed contact closure for automatic NC test advance, or periodic data recording applications.

PRICE: Model 5525A (Includes Model 5500A Interferometer Head, Model 5505A Display, and Model 10550A Reflector), **$11,500.00.**

MANUFACTURING DIVISION: SANTA CLARA DIVISION
5301 Stevens Creek Boulevard
Santa Clara, California 95050

André F. Rudé

A former sports car and motorcycle racer and light airplane pilot, André Rudé settled down after his marriage and now only climbs mountains and skis. He also fixes and collects old clocks. Appropriately, when he joined HP in 1966, his first assignment was in the product design of frequency and time standards. He subsequently took on the product design responsibility for the new laser interferometer, and is now looking into new ways of using the interferometer in metrology and other fields. André is a member of ASME.

Kenneth J. Wayne

Keeping his head above water isn't one of Ken Wayne's problems; he's a scuba diver and underwater photographer with a strong interest in oceanography. Ken did the optical design and some of the mechanical design of the new laser interferometer, and has recently switched to marketing as the western region field engineer for the interferometer. Ken began his career designing jet engines, then came to HP in 1964. His BSME degree is from the University of Arizona.

A New Tool for Old Measurements – and New Ones Too

By André F. Rudé and Kenneth J. Wayne

Although Model 5525A Laser Interferometer measures distance and velocity with great range and accuracy, it is nevertheless practical and economically justifiable to use it for making gross low-accuracy measurements, since it is fast and easy to use. The diagram illustrates the spectrum of its applications.

The primary application is in **calibration of numerically controlled machine tools and coordinate measuring machines** in the machine shop and metrology lab. The laser beam can be aligned parallel to the axis of a machine tool or measuring machine in a few minutes. Because the system requires no warmup, calibration may begin immediately. Complete calibration of a three-axis machine tool with a printed record and/or a graph of errors versus command position can be accomplished in a few hours, compared with days by conventional methods. What's more, conventional methods do not automatically generate a graph. No specially trained personnel are needed, since the new interferometer is very simple to operate.

New for a laser interferometer is the ability to measure the axial growth of a rotating spindle due to frictional heat in its bearings. The cube-corner reflector is chucked and spun in the spindle and the beam is aligned parallel to the axis. This cannot be done with a conventional interferometer because, when the nonreflecting edges of the cube corner pass through the beam, the optical signal drops below the level at which the counter can safely trigger. The new interferometer, however, can tolerate a 95% loss of optical signal without error, so the small amount of light lost as the cube-corner edges go through the beam is hardly even noticed.

Since this laser interferometer also measures velocity, it is possible to **calibrate machine tool feed rate** at the same time positioning accuracy is measured.

In the metrology laboratory the new interferometer is useful for **calibration of other length standards** such as micrometer heads, tool-makers' microscopes, glass and metal scales, and even low-accuracy steel tapes over 200 feet long. With suitable fixturing it can be used for parts inspection.

It is particularly noteworthy that metrological calibrations may be performed continuously rather than in discrete steps as required with gage blocks. The HP error plotting option generates a continuous plot of leadscrew error versus position that allows the metrologist to see short-term variations in lead (leadscrew drunkenness) which otherwise might be obscured by the 'synchronous sampling' of gage blocks. Also the error incurred by transferring a measurement from a part to a stack of gage blocks can be avoided.

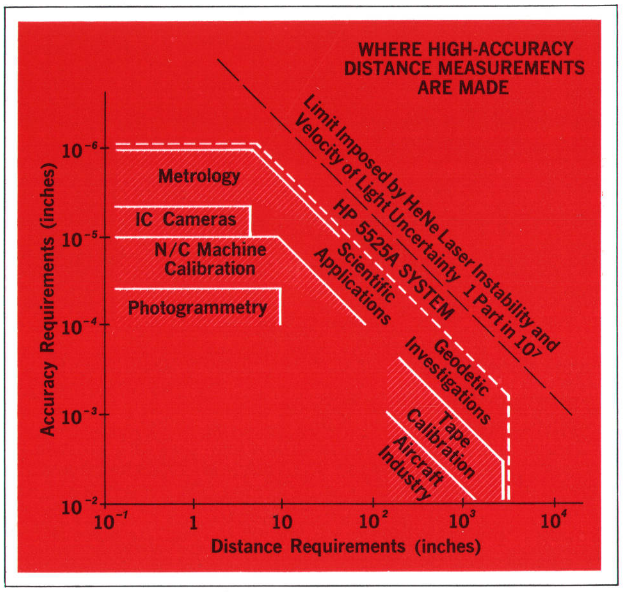
In keeping with the present trend toward **on-the-machine inspection,** the new interferometer is a natural for use as a length standard. The machine tool is converted to an N/C measuring machine by replacing the cutting tool with a contact probe and using the laser interferometer as the position transducer. The same tape used to machine the part is used to control the inspection process. A part may be inspected in its fixture immediately after machining.

Model 5525A Interferometer is already used as a **precision option on conventional N/C machine tools** that have their own built-in position transducers. With this arrangement it is possible to machine to normal tolerances with N/C. Then, for precision machining, the controller turns the machine over to the operator who manually positions one axis at a time using the laser interferometer. An example of this use might be precise locating of dowel holes in a large part. With the aid of beam benders, a single HP interferometer in a fixed mounting location can be used to position all axes of a machine.

From here it is only a short step to complete **closed-loop N/C or computer control** of the machine tool.

Other applications for the new interferometer are in control of step-and-repeat cameras for integrated-circuit production, in control of artwork generators, in mapmaking, and in photogrammetry. Stress-analysis and thermal-expansion-coefficient measurements of interest to the mechanical engineer and metallurgist are easily made, and physicists can make index of refraction measurements. A new and still experimental application is predicting earthquakes by accurate long-term measurements of earth movement in fault locations.

As for the future, who knows what is possible when you can measure a microinch?



Automatic Error Plotting—a Report Card for Nonlinear Behavior

By Jonathan D. Garman

IN ALMOST EVERY CALIBRATION OF A LINEAR SYSTEM, the desired result is a plot of system error as a function of some calibration parameter. In the case of machine tool calibration, the calibration parameter is the nominal or command position of the machine tool along one of its axes, and the error is the difference between the actual position and the command position.

Although laser interferometers have greatly increased the accuracy and speed of machine-tool calibrations, methods of deriving errors and presenting them graphically have been largely unsatisfactory, ranging from tedious manual methods to complex, expensive automatic systems.

The main stumbling block in the automatic approach is that the command position of the machine tool is awkward to obtain in electrical form. In manual machines, of course, the command position is simply not available. In some automatic machines it is available, but codes are not standardized and vary from machine to machine. Even when the command position is available in electrical form, dozens of interconnections are required to make use of it.

New Error Plotting System

The HP approach doesn't solve these problems, it sidesteps them by making a few nonrestrictive assumptions about machine errors. As a result, automatic error plotting becomes a simple task, requiring only an inexpensive plug-in option for the interferometer, a single two-wire cable to the machine tool, and an X-Y recorder. The only signal required from the machine is a simple synchronization pulse to signify that the machine is in nominal position on a calibration point.

The principal assumption made in implementing the error plotting system is that the largest error to be encountered will be less than half the interval between calibration points. If the errors prove to be larger than this, the interval can be widened appropriately. The interval between calibration points can be any integral multiple of 0.010 inch and the range is 100 inches. Longer scales can be calibrated in 100-inch segments. If the interferometer is operating in the extended-resolution mode all these numbers are divided by 10. The full-scale position is selectable, and accuracy is constant (approximately 0.5% of reading) whether full scale is one inch or 100 inches.

How the system works is best explained by an example. Suppose that a positive error exists at three calibration points and the interferometer readings are 4.00012 inches, 4.10017 inches, and 4.20023 inches. The error plotting system breaks each reading into two parts and assumes the right-hand part is the error and the left-hand part is the command position. It then plots each right-hand part as a function of each left-hand part. Thus 12, 17, and 23 are assumed to be the errors in tens of microinches at the calibration points 4.00000 inches, 4.10000 inches, and 4.20000 inches, respectively. In other words, the system derives both command position and error just by inspecting the interferometer display. There is no need for complicated computations and massive interfaces.

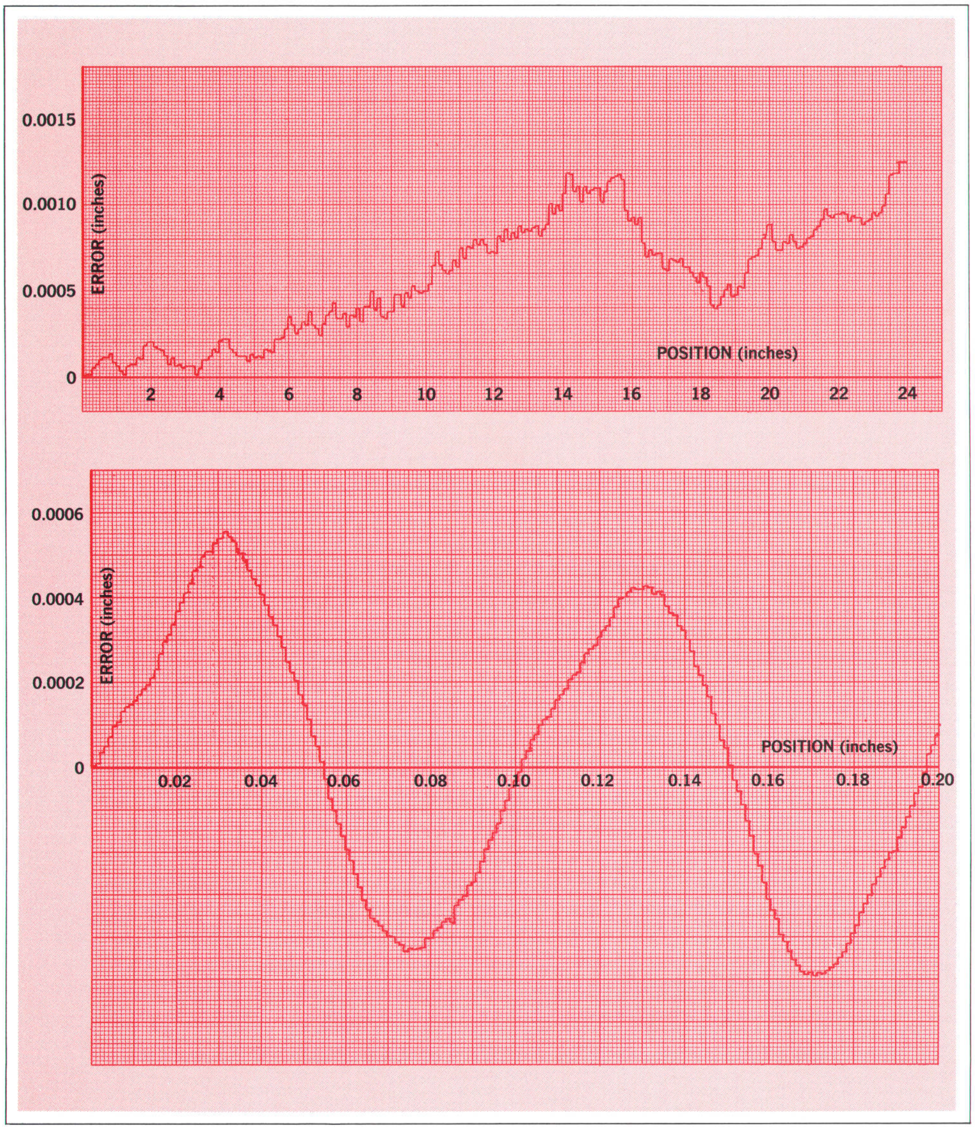
When negative errors are encountered, the right-hand digits are complemented to obtain the correct absolute value of the error. The left-hand digits are incremented by one unit so the error will not be plotted one step too low.

Modes of Operation

The error plotting option operates in one of several modes, depending upon the type of machine being calibrated. For a full N/C machine tool, a command tape is prepared to position the machine sequentially to the desired calibration points.* The interferometer contacts are clipped in parallel with the manual-step button. The contacts step the machine through the control tape point-by-point, plotting the position and error at each calibration point. The stepping rate is front-panel selectable.

When calibrating a manually controlled machine such as a manual milling machine, the machine is placed in control of timing. A pulse must be generated each time the machine moves one calibration interval. This can be (and has been) done either by having a microswitch drop

* Some newer N/C controllers don't require the command tape.



Graphic displays, like these generated by the error plotting option for Model 5525A Laser Interferometer, show machine errors in perspective. Both plots were made during a calibration of one axis of a numerically controlled milling machine that was suspected of being out of specification over large distances. The top plot shows the error at 0.1 inch intervals over the entire 24-inch axis. The upward slopes reveal that the machine's three 10-inch internal scales are all long by 50 parts per million. The rightmost scale is also 0.0005 inch out of position, as shown by the downward step, which is broadened by the effect of the machine's three-inch-wide read head. Plotting time was four minutes. The bottom plot magnifies a 0.2 inch section of the same scale, showing the error at 0.001 inch intervals. There is a cyclic error with a peak value of 0.0005 inch, indicating misadjustment of the electronic circuits which interpolate between the 0.1 inch marks of the machine's inductive scales. Similar cyclic errors are often seen on leadscrew machines and micrometers.

into teeth on a gear on the drive leadscrew, or by a lamp-photocell combination looking through a slotted disc driven by the leadscrew. The pulse commands the interferometer to make a measurement and plot the error. Measurements are taken on the fly, that is, without stopping the machine at each calibration point.

When it is impractical to generate an automatic synchronization signal, the synchronization can be done manually. This might be necessary, for example, in calibrating a precision microscope stage or a micrometer. The operator would position the instrument manually, and when ready he would press the MANUAL PLOT switch to plot the error.

Acknowledgments

The error plotting option was developed jointly with Gary Gordon, who originally proposed the technique.

Jonathan D. Garman

Jon Garman's first instrument netted him his first patent application—one on the error plotting system for the 5525A Laser Interferometer, co-authored by Gary Gordon. Jon's efforts in logic design for the interferometer also earned him the job of project leader for the forthcoming automatic velocity-of-light compensator for the 5525A. A 1967 recipient of a BSEE degree from Stanford University, Jon did graduate work at the University of Illinois before joining HP in 1968. He's an amateur trumpet player and photographer, but his first love these weekends is the old Jaguar XK140 he's restoring. That's the Jag's cylinder head in the foreground.

Machine Tool Evaluation by Laser Interferometer

By Richard R. Baldwin

INCREASING DEMAND FOR HIGH ACCURACY in mass-produced machined parts has forced the machine tool industry to rely less on the skill of the machinist and more on the accuracy of the machine tool itself. The large number of identical machining operations required for mass production has led to increasing automation of machine tools, ultimately leaving the machine tool responsible for the quality of the finished part. This, of course, has made it imperative that builders and users of machine tools continuously study and improve their tools' operating characteristics, particularly positioning accuracy.

One of the earliest problems associated with machine tool evaluation was the lack of a suitable length standard. Evaluation of positioning accuracy was commonly performed using a physical standard such as a scale or lug bar. These were available with sufficient accuracy in lengths up to about two feet, but longer standards were unwieldy and generally inaccurate. This meant that positioning accuracy of large machine tools had to be checked in short intervals by the method of 'staging' which was an extremely long and tedious process. The results so obtained were often nonrepeatable, and were not always indicative of the accuracy of the machine tool under evaluation.

The development of the laser interferometer finally provided the machine tool industry with a high accuracy length standard which could be used on machine tools of all sizes. The accuracy of the interferometer is limited by the laser wavelength, which is known to within about one part in ten million. This value compares favorably with the best physical standards available, and is certainly adequate for machine tool evaluation. In addition, the laser interferometer is extremely easy to use, allowing measurements to be made in minutes which had previously taken several hours or even days to perform.

Initial attempts at machine tool evaluation using the laser interferometer yielded results very quickly, but again the results were often nonrepeatable and not indicative of machine tool positioning accuracy.

Wavelength Variations

One reason for this involves the wavelength of the laser itself. It is the wavelength in vacuum which is known to about one part in ten million. The wavelength in air is somewhat shorter than the vacuum wavelength, since air has a refractive index slightly greater than one. In addition, the refractive index of air is not constant but is a function of air composition, temperature, and barometric pressure. To define the wavelength of the laser in air, therefore, all of these factors must be accurately determined. For this reason, all commercially available laser interferometers with fringes-to-inches conversion have provisions for determining barometric pressure, temperature, and relative humidity either automatically or via manual input.

Many users of interferometers, however, do not realize that these systems include a combination of electronic circuits and transducers which are subject to failure, and which require periodic recertification. In addition, many interferometers are built in such a way that certification of the pressure, temperature, and humidity correction factors is an extremely tedious and difficult process. This is particularly true in interferometers with automatic wavelength correction. As a result, many users do not institute an adequate recertification program for their interferometers, and this generally results in inaccurate measurements due to improper fringes-to-inches conversion.

Thermal Effects

Another and more significant source of error in interferometer machine tool evaluation is the effect of temperature on the machine tool itself. For machine tools which use a steel leadscrew to determine carriage position, this effect represents an expansion of six microinches per inch for a one-degree-Fahrenheit rise in the leadscrew temperature. If the total carriage travel were 50 inches, this effect would represent a total change in positioning accuracy of 300 microinches for each degree change in the leadscrew temperature. Further compounding the difficulty is the fact that the leadscrew operates in an extremely poor thermal environment. During operation, the leadscrew is faced on all sides with heat sources such as the driving motor, the bearings, and the drive nut.

During the first few hours of machine operation, the leadscrew temperature increases to some value well above ambient. Its final temperature, however, is not only a function of the ambient temperature but is also dependent on how the machine is operated during warmup. If the carriage is cycled on fast feed through its entire travel, for example, the leadscrew temperature will stabilize at a higher value than would result during normal operation. It is therefore important that the conditions under which a machine tool evaluation is made be well controlled and well defined. But even more important, it should be recognized that the machine tool will probably *not* show the same characteristics during actual operation. The presence of coolant, the use of different feed rates, cutting forces, and many other factors will change the positioning accuracy of a machine tool during use. A machine tool evaluation should therefore be conducted under conditions which best approximate those conditions under which the machine tool will operate during use.

An additional temperature effect occurs in the machined part itself. It cannot be assumed that the machined part will remain at ambient temperature during the machining process, and if the part is not at ambient temperature its dimensions will change due to thermal expansion or contraction when it is taken off the machine. This effect is not directly applicable to machine tool evaluation since it is due to no fault of the machine tool, but it must be understood by the machine tool user if he wishes to obtain optimum machine tool performance.

Mechanical Deflections

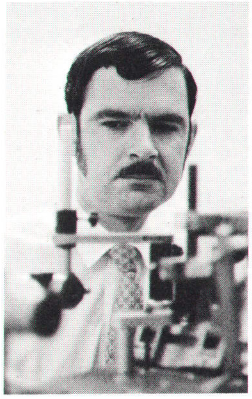
In addition to thermal effects, mechanical deflections of machine tool components often introduce error during a machine tool evaluation.

As an example of machine tool deflection, the author witnessed some time ago a series of interferometric machine tool tests in which the interferometer sensing head was mounted on a large tape-controlled lathe by means of a platform which replaced the tailstock. This platform provided a stable, vibration-free mounting fixture which appeared to be adequate. However, when the data obtained relative to the tailstock were compared to similar data taken relative to the spindle, certain repeatable differences became apparent. A detailed examination of the setup revealed that as the carriage approached the tailstock platform, which supported the interferometer, the platform was deflected toward the carriage by an appreciable amount. This deflection was due to bending of the entire machine bed, caused by the weight of the carriage. It would not have been valid to accept or reject the machine tool on the basis of data taken relative to the tailstock, since it is the position of the tool tip relative to the spindle which determines machining accuracy. In this case, deflections of the machine bed should have been taken into account when designing fixturing for the laser interferometer.

Despite the insidious nature of the previous example, it is one of the simpler types of machine deflection. Besides the predictable deflections caused by the weight of moving components, there exist much more complex deflections caused by thermal gradients throughout the machine tool. These effects are not constant, and are a function not only of the conditions under which the machine tool is operated, but also of the environment in which the machine tool operates. Here again, it is important that the conditions under which a machine tool is evaluated approximate those conditions under which it will be used.

In conclusion, it should be mentioned that the previously described problems are not new, nor are they unique to the laser interferometer. The same principles apply when using any measuring system. The point is that the laser interferometer does not eliminate the fundamental requirements of precision measurement. Machine tool errors are complex by nature, and can only be eliminated through intensive study. The laser interferometer represents a valuable tool for diagnosing these errors, which is the first step in improving machine tool performance.

Richard R. Baldwin



Dick Baldwin is well on the way to making a name for himself in the fields of precision optics and precision machining. During the past seven years, Dick has been involved in the design and application of optical measuring systems to meet high accuracy requirements; has been a consultant in machine tool evaluation, error mapping, and correction; has designed and fabricated physical standards for machine tool certification; and has helped develop new methods of machining with diamond tools. He is the author of several papers and patent applications related to laser interferometry and precision machining. At HP for the last year, Dick has been developing methods for evaluating high precision optical components and machine tools. Dick holds a BS degree in engineering physics from Ohio State University and is a member of the Society of Manufacturing Engineers.

An Instant-On Laser for Length Measurement

This specially developed two-frequency laser is rugged, tunes itself instantly, and runs cool.

By Glenn M. Burgwald and William P. Kruger

SOON AFTER ITS INVENTION ten years ago, some clever fellow characterized the laser as 'a solution looking for a problem.' That solution has now found problems aplenty, ranging from eye surgery through metal cutting to high-density data storage and retrieval, to name but a few. Another such problem is the precise measurement of distance, made feasible by the coherence and accurately known wavelength of laser light. When a laser is used as the light source in an interferometer, distance measurement is a simple matter of counting interference fringes, each count signifying another few millionths of an inch of distance.

For the new HP Laser Interferometer described in the article on page 2, an entirely new laser was developed. Designed specifically for interferometry, it is a single-mode helium-neon laser in which Zeeman splitting is used to divide the main spectral line into two lines separated in frequency by about 2.0 MHz. The laser is extremely rugged, can be locked on frequency without warmup, and is designed to operate reliably in industrial use for 10,000 hours or more.

Single-Mode Operation

To avoid ambiguity in translating light wavelengths into distance, the laser operates in a single transverse mode and a single longitudinal mode. It has a 'hemispheric' mirror system in which a flat and a spherical mirror face each other at opposite ends of a gas-discharge bore of predetermined length and diameter. By adjusting mirror spacing, diffraction losses are set so that only the lowest-order transverse mode, TEM_{00}, can oscillate. Fig. 1 illustrates power output versus mirror spacing for a given bore diameter, and shows typical mode bounds. The laser operates as high on the power curve as possible without danger of developing spurious transverse modes.

Single-longitudinal-mode operation is achieved by using a mirror spacing of approximately 13 cm, a value sufficiently small to keep adjacent modes in regions of low gain and thus prevent their simultaneous oscillation. Fig. 2 shows how laser gain varies with frequency for the Doppler-broadened 6328Å (632.8 nm) line of helium-neon. Mode spacing is $c/2l$, where c is the velocity of light and l is the mirror spacing. A proper choice of l is one which safely suppresses adjacent modes when some one mode is at maximum gain. But with l/R constant (R is mirror radius of curvature) smaller l means smaller output power. Optimum spacing is 13–15 cm.

Zeeman Splitting

Although single-mode operation is necessary to avoid ambiguities, a better interferometer can be built if two adjacent frequencies are available rather than a single one (see article, page 2). In the new HP laser, two frequencies are obtained by Zeeman splitting of the main spectral line. Here's what this means.

If an axial magnetic field is applied to a laser which is free from polarization anisotropy in either the mirrors or the plasma tube, the output splits into two frequencies of left and right circular polarization as shown in Fig. 3. First-order theory predicts that the frequency splitting is proportional to magnetic field strength and to the ratio of line Q to cavity Q. In the new laser, magnetic field strength is adjusted for a difference frequency of about 2.0 MHz. Line center is virtually midway between the displaced lines, so proper cavity tuning can be assured by adjusting for equal intensities of the lines.

Fig. 4 is a photograph of the interior of the laser head, showing the axial magnet.

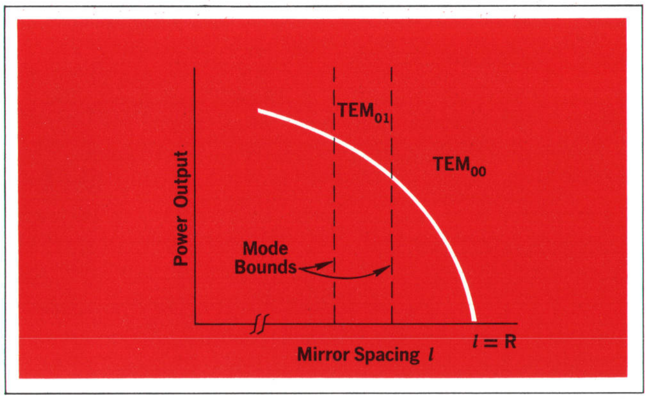


Fig. 1. *Laser power output versus mirror spacing for a given diffraction aperture (bore diameter), showing typical transverse-mode bounds. New HP laser operates in TEM$_{00}$ mode only, but as close to TEM$_{01}$ region as possible, so as to maximize power output.*

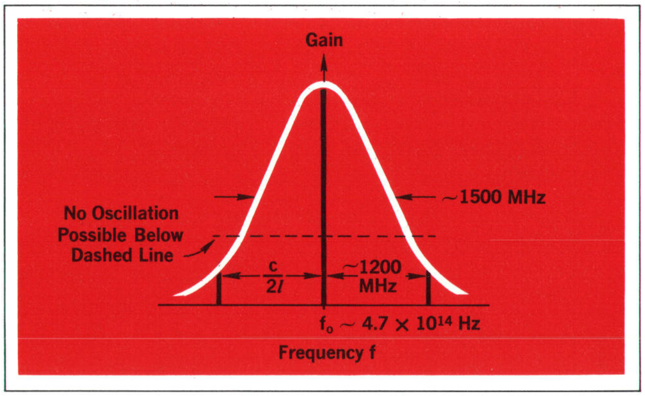


Fig. 2. This is the Doppler-broadened gain curve for the *6328Å (632.8 nm) line of helium-neon. In the new HP laser, cavity length (l) is about 13 cm, so only a single longitudinal mode can oscillate.*

Cavity Design and Tuning

The requirement of no polarization anisotropy, which must be satisfied for Zeeman splitting, precludes use of a plasma tube with Brewster-angle windows, since such windows have low reflection loss for only one kind of polarization. This in turn means that internal mirrors are obligatory. Also, it was a design objective that the laser be tuned to line center as soon as it is turned on, and this means that the plasma tube, or cavity, must include a tuning element to compensate for small changes in length.

The cavity design satisfies both these requirements. A sturdy rod, about an inch in diameter, of one of the new inorganic materials having virtually a zero coefficient of thermal expansion, is used as a combined plasma tube and mirror spacer. It has an axial hole of the proper size to control transverse-mode excitation, and the ends are precision-ground to provide proper mirror alignment.

Cavity length changes during and after warmup are small enough to be compensated by a piezoelectric wafer which forms part of an electronic servo loop. The loop monitors the intensities of the Zeeman-split lines and keeps them equal by varying the voltage on the piezoelectric element. The tuning range is adequate to compensate for all expected thermal length changes without the need for an oven.

This very stiff and stable resonator is encased in an all-glass envelope through which are brought appropriate electrical leads to generate a gas discharge and to apply voltage to the piezoelectric tuning element. Since no organic cements are used, the laser can be given high-temperature vacuum bakeout before final filling. This removes gas contamination as a factor tending to reduce the life of the laser.

Long-Life Mirrors

Because of the modest gain-per-pass in this type of laser, photons must be reflected back and forth many times through the cavity to achieve oscillation, and hence the mirrors must have extremely good reflectivity. Only tuned multilayer dielectric surfaces have the needed reflectivity at optical wavelengths. These coatings must be able to withstand evacuation, high-temperature bakeout, and exposure to all radiation from the discharge including ultraviolet. Unfortunately, the 'soft-coated' mirrors typically used externally, although excellent reflectors, deteriorate upon exposure to ultraviolet light in at most a few hundred hours.

Coating manufacturers have exerted a great deal of effort to achieve 'hard' coatings unaffected by ultraviolet light, and have found that alternate layers of silicon dioxide and titanium dioxide, for example, can provide adequate reflectivity and yet not deteriorate from ultraviolet exposure. They also withstand the thermal cycling of good vacuum practice. The new laser has mirrors of this type. Long-term life tests are under way, and some are now approaching 20,000 hours. Therefore, it seems possible to conclude that hard-coated mirrors properly made and used do not limit laser life.

Long-Life Discharge

Eliminating the most common cause of laser failure—contamination of the fill gases—does not in itself assure infinite laser life. Mechanisms exist by which the noble gases helium and neon can be lost to the discharge. For instance, helium diffuses rapidly through certain glasses. To minimize this, the new laser's envelope is made of a material which is very low in helium diffusion.

A different kind of loss involves 'capture' of noble

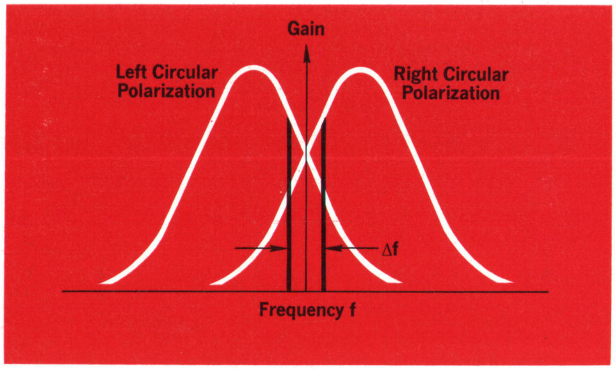


Fig. 3. *Two frequencies are derived from the single-mode laser by Zeeman splitting. An axial magnetic field causes the single line to split into two lines. The two frequencies have opposite circular polarizations.*

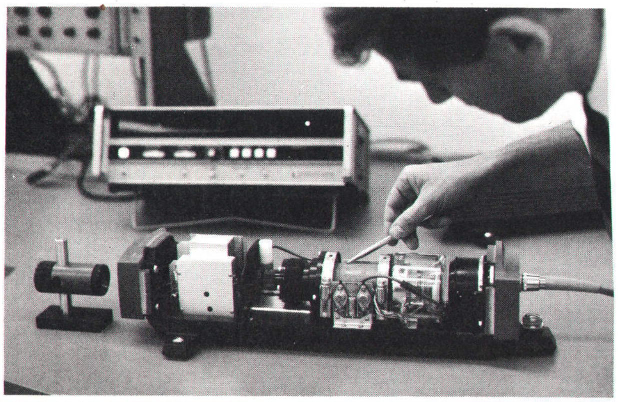


Fig. 4. *Interior of laser head, showing laser with axial magnet, telescope, and interferometer components. Pencil points to magnet.*

gases either within the metallic lattice of the cathode by ion penetration, or through a complex sputtering process which seems to plate out gas atoms when cathode material migrates to a new surface. In the new laser 'capture' factors are minimized by proper cathode design and fill pressures. The laser uses a cold cathode of rugged design whose long life has been demonstrated.

Acknowledgments

The laser described was developed in the physical electronics laboratory of Hewlett-Packard Laboratories. The two-frequency system and means for achieving suitable two-frequency operation were suggested by Len Cutler, Al Bagley, and Don Hammond. Means of drilling and grinding the zero-expansion cavities were perfected by Vas Peickii and personnel of the HP Laboratories model shop. Envelope construction fell to Bob Lorimer of the HP Laboratories glassworking shop. Innumerable ideas and suggestions were contributed by others including Hugo Fellner, Joe Rando, Wright Huntley, and Howard Greenstein.

William P. Kruger

Farmhand, newspaper editor, grocer, college professor, research physicist—Bill Kruger has been all of them. At HP since 1959, Bill was manager of cathode-ray-tube design for several years. More recently he helped invent the new two-frequency laser, and now, as a physicist on the staff of Hewlett-Packard Laboratories, he is doing research on lasers, beam-switched diodes, and spectrometers. He has five patents, mostly on gas-filled tubes. Bill holds BA and MS degrees from the University of North Dakota and has done graduate work at the University of Illinois and the University of Chicago. He is active in the Involvement Corps and other community groups, and thinks that woodworking and golf are the perfect ways to relax.

Glenn M. Burgwald

Glenn Burgwald has been working with radiation and optics for his entire professional career, which began in 1948 with a BSEE degree from the University of Illinois. Today, eight papers and three patents later, he is providing technical support as production of the new two-frequency laser he helped invent gets under way. At the same time, he is continuing to do research aimed at further advances in laser technology. Glenn joined HP in 1965, contributed to the development of the laser, then left for a while but returned in 1969 to participate in the interferometer project. Glenn's three years with the U.S. Air Force seem to have left a permanent mark—he has a passion for radio-controlled model aircraft. He keeps in shape by playing tennis.

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