THE BELL SYSTEM
TECHNICAL JOURNAL

Volume 47 February 1968 Number 2

Optical Heterodyne Experiments with Enclosed Transmission Paths

By O. E. DeLANGE and A. F. DIETRICH

(Manuscript received September 13, 1967)

Experiments to determine the feasibility of using optical heterodyne receivers at the end of long and complicated transmission paths showed that nearly ideal performance is possible. The paths were enclosed, thus avoiding atmospheric turbulence. We set up two receivers, one coherent and the other noncoherent, and compared their signal-to-noise performances and stability. The degree of beam distortion resulting from transmission over a path was determined by comparing the path losses as measured by the two receivers. Heterodyne detection was nearly 80 per cent efficient for a four-mile path involving 63 reflections and transmission through a considerable number of other optical components. Stable heterodyne operation was observed.

I. INTRODUCTION

It is well known that efficient operation of a light heterodyne receiver requires a high degree of phase coherence between the received signal beam and the local oscillator beam.[1] For example, if the angle between the received beam and the local beam is in error by as little as one second of arc there can be considerable loss of signal. Also it is obvious that if the beam were translated by a beam width the detection efficiency would be reduced to zero. These requirements are so critical that many declared successful operation of a heterodyne detector at the end of a long transmission line to be very doubtful.

Experiments on the transmission of light beams through the open atmosphere have shown that atmospheric turbulence might render the beam unsuitable for heterodyne detection.[2] However, the medium which we visualize for long-distance optical transmission consists of a series of lenses or mirrors for guiding the beam through an enclosure which isolates it from its environment. It is quite likely that successful guided transmission will require some type of beam position servo control in some of the guiding elements. If we provide this control, the position of the received beam can be stabilized so that an efficient heterodyning adjustment, once made, will be maintained. Stabilizing the position of the received beam automatically stabilizes its angle of arrival. During some previous experiments[3] we observed that single-mode transmission appeared to be preserved even after many reflections. Because of these favorable considerations, we decided to set up an experimental heterodyne receiver at the end of the longest transmission path available and observe its operation.

II. THE EXPERIMENTS

2.1 *Transmission Path*

The path consisted of a horizontal aluminum tube six inches in diameter and 100 meters long. We put eight concave mirrors, one inch in diameter, at one end of this pipe and seven at the opposite end to transmit a laser beam for eight round trips through the line. The total distance was one mile through enclosed atmosphere.

2.2 *Experimental Arrangement*

Fig. 1 shows the experimental arrangement in block form. The laser, which operated at 0.63μ, was in a cavity only 20 cm long. This means it could oscillate at only one frequency as long as it was kept tuned near the center of the doppler line. Temperature stabilization of the cavity was sufficient to assure single-frequency operation without automatic frequency control. Power output was approximately one milliwatt.

The laser ouput was amplitude-modulated a few percent by applying an 84 KHz sine wave to a modulator which consisted of a suitably-oriented rod of KDP followed by an analyzer. The combination of a lens and a concave mirror constituted a telescope for adjusting the beam diameter and radius of curvature properly for launching it into the pipe line. The flat mirror between the lens and the curved mirror served only to fold the path back on itself. See Fig. 1. The tilt

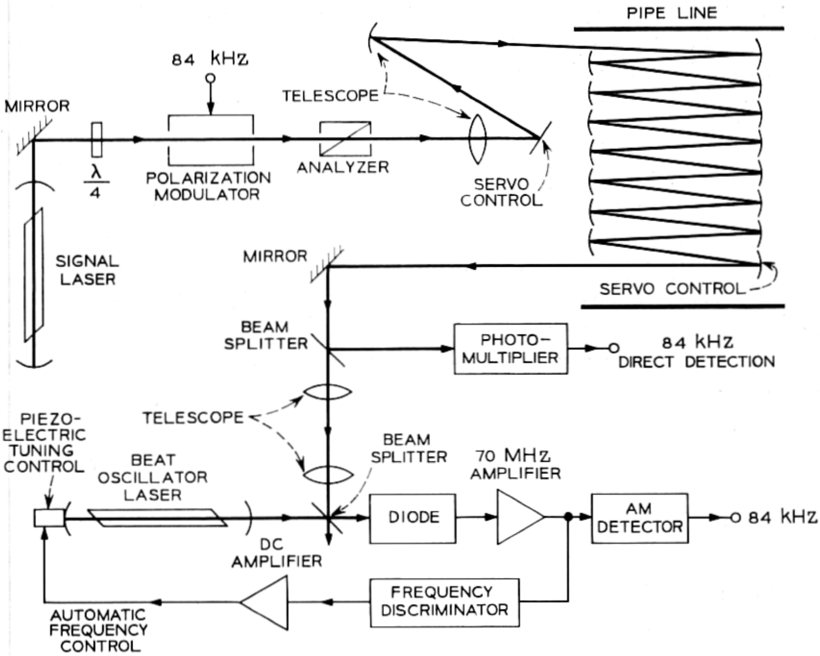

Fig. 1 — Experimental arrangement, one-mile path.

of the flat mirror was controlled by voltages applied to two piezoelectric cylinders. This was part of a servo system used to assure that the beam was properly directed to arrive at the center of the mirror at the far end of the line.

After eight round trips through the line the emerging beam, whose position was also servo-controlled, was directed along two separate paths by a beam splitter. One path included a photomultiplier functioning as a direct detector for recovering the 84 KHz modulation. The second included a telescope for reducing the beam diameter and converting it to a nearly plane wave. This wave was combined with the beam from the local laser on a second beam splitter. One output from this beam splitter was focused onto a photodiode detector. A 70 MHz intermediate frequency was obtained from this detector as a result of the beating of the two signals. The amplified output of the 70 MHz receiver was applied to a diode detector from which the 84 KHz modulation was recovered. A 70 MHz frequency discriminator furnished an error voltage for automatic frequency control of the local oscillator laser. The amplified error voltage was fed back to a piezoelectric mirror mount in such a way as to maintain the frequency difference between the two lasers at 70 MHz.

The beam emerging from the line was centered between four sensors as shown on Fig. 2. The error voltage from these sensors was amplified and applied to piezoelectric cylinders which controlled the tilt of the last mirror at the far end of the line and thus kept the received beam centered. The remaining mirrors in the line were not servo controlled but had manual electrical tilt adjustments.

The direct detector consisted of an RCA 7326 photo-multiplier tube with a circuit in its anode tuned to pass 84 KHz. Because of the gain in the multiplier section of this tube it was possible to make the signal and shot noise power so much greater than thermal noise that the thermal noise could be neglected. The cathode of this tube is large enough to make signal output largely independent of beam position for moderate amounts of beam translation. The heterodyne detector was a Texas Instrument LSX 900 photodiode. A transformer tuned to a center frequency or 70 MHz coupled this diode to the input of a low-noise preamplifier. The transformer and amplifier had

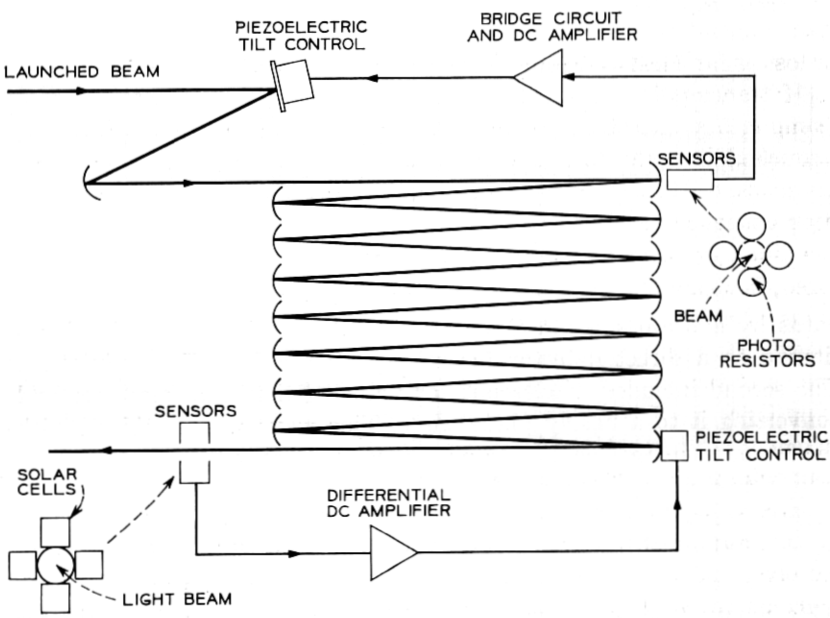

Fig. 2 — Servo-controlled beam positioners.

a bandwidth of approximately 20 MHz. The active area of the diode was only 0.01 inches in diameter which meant that the beam had to be very accurately centered on it for maximum response.

2.3 *Determining Heterodyne Efficiency*

The basic plan for the experiment was to measure the loss introduced by the line as indicated by the heterodyne receiver and to compare this with the line loss indicated by the direct detector. If the transmission loss indicated by the heterodyne receiver is greater than the loss measured by a direct detector the difference can be attributed to a decrease of detection efficiency for the heterodyne receiver resulting from distortion of the wavefront of the beam by transmission through the line. Such distortions should not affect the direct detector.

This can be stated differently by noticing that transmission over the long path results in some of the light power being converted into higher order modes by any existing line imperfections. That power converted to very high order modes cannot propagate in the line and is lost. Some of the lower order modes can propagate and will be detected by the direct detectors, whereas the heterodyne detector can respond to only one mode so that any power not in that mode is lost as far as this detector is concerned.

If transmission of the beam through the required external optical components produced wavefront distortion before the beam was launched into the line, the distortions introduced by the line might be masked. Because of this we need to determine the absolute detection efficiency (at least with respect to the beam as it is launched into the line). Detection efficiency is defined as the ratio of actual, or measured, beat-note current to the current calculated for an ideal detector. This efficiency can be measured in several ways. First if the signal power, P_s, the quantum efficiency, η, and the bandwidth B are known, we can calculate the expected carrier-to-noise ratio from the relationship $C/N = \eta P_s/hfB$ where h is Planck's constant and f the light frequency. By comparing the measured C/N to the calculated value we can determine detection efficiency.

The C/N for the heterodyne receiver was measured by means of a detector at the IF amplifier output. With a light signal into the receiver the IF gain was adjusted to produce some value of detected current to serve as a reference. The signal was then removed and the IF gain increased until the detector produced the same amount of current, this time resulting from the noise. This change of gain was equal to the C/N. Because the equation applied only to shot noise, it was necessary to correct for the presence of thermal noise. With the heterodyne gain obtained for this experiment shot noise and thermal noise powers were comparable.

The second method of determining efficiency was to compare the amplitude of a low-frequency beat note (produced by beating the unmodulated signal with the local oscillator) with the dc output of the diode detector. It can be shown that, ideally, when the oscillator power, P_o, is much greater than the light signal power, P_s, the ratio $I_B/I_{DC} = 2(P_s/P_o)^{1/2}$. I_B is the peak current at the beat note frequency. The ratio of measured I_B to calculated I_B is the detection efficiency.

The beat note method consistently indicated a higher efficiency than the C/N method. Unaccounted-for noise or the cumulative effect of errors in determining the light-signal power, quantum efficiency, and bandwidth, could account for the pessimistic C/N measurements.

We also made some optical tests to determine the heterodyne efficiency. Because heterodyne deficiencies result from lack of phase coherence between the signal and local oscillator beams, it is evident that restricting the area of the superimposed beams to a small region near their centers improves coherence. And if this area is made sufficiently small, perfect coherence must result. Hence, if the combined beams are passed through a small iris before being applied to the detector, a reference value corresponding to 100 per cent efficiency should be obtained. If perfect coherence exists over the total area of the beams, increasing the diameter of the iris will not affect the efficiency and the manner in which the IF output increases with iris area is predictable. If perfect coherence does not exist, increasing the iris diameter will reduce the detection efficiency and the IF output from the detector will not increase as much as expected.

For our experiment we used detected direct current as a criterion of iris area. Direct current from the detector increases linearly with combined local oscillator and signal power. The intermediate frequency power is proportional to the product of the two light powers and should vary as the square of the direct current. Fig. 3 is a plot of the results of varying the iris diameter in such an experiment. The dashed line shows the ideal variation of IF power with detected direct current, that is, the variation which should be expected for perfect phase coherence between the two beams.

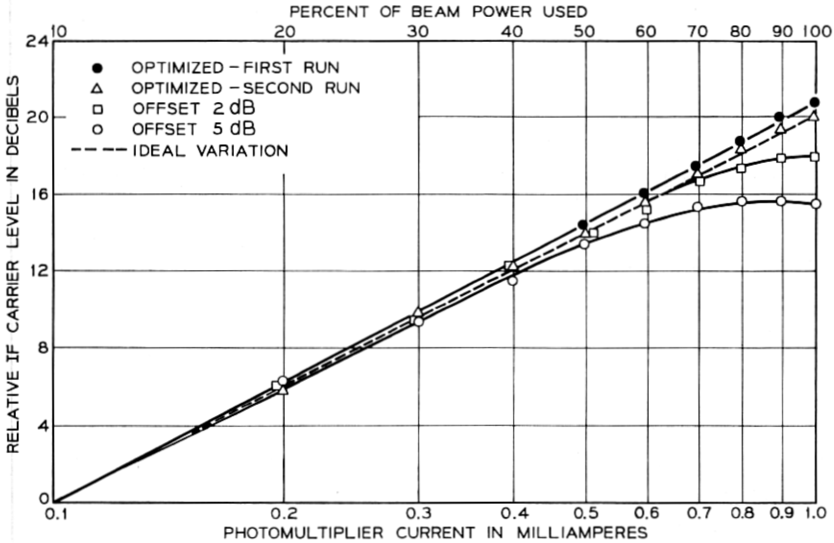

Fig. 3 — Phase coherence tests comparing 2 and 5 dB offsets.

The solid curve with dots shows actual performance after the detector had been adjusted to produce maximum IF power. The performance is close to ideal. Next, the received beam was tilted from the local oscillator beam to reduce IF Power by 5 dB with the iris fully open. The curve with circles shows how IF power varied with diaphragm opening. The effect of lack of coherence is quite evident from the saturation of IF carrier as the iris opening was increased. This test was repeated with a 2 dB offset, corresponding to 80 per cent efficiency. The curve with squares indicates the results.

III. EXPERIMENTAL RESULTS

3.1 *One Round Trip*

To evaluate the effect of components outside the line, we first measured the detection efficiency for only one round trip through the line. For this arrangement the signal beam traversed one KDP modulator, one Glan-Thompson prism, one short focal length lens, two spherical mirrors, two flat mirrors, two quarter-wave plates and two beam splitters. All of these components were stock items with no attempt to obtain exceptional quality. The C/N method indicated a detection efficiency of 81 per cent, the beat note method 98 per cent; the true value is probably somewhat between. Evidently there was no serious deterioration of performance even though the beam returned from the line was noticeably elliptical in contrast with the circular beam from the beating oscillator.

3.2 *One-Mile Line-Losses*

By adding 14 more spherical mirrors to the optical path mentioned above the path length was extended to eight round trips for a total distance of one mile. The efficiency, determined from a number of measurements of C/N, averaged 81 per cent; the beat note method averaged 87 per cent. These data indicate that addition of the seven round trips to the optical path did not appreciably reduce the detection efficiency. This is borne out by the results of another series of experiments in which the line losses, as indicated by the heterodyne receiver, were found to be the same as the losses measured with the direct detector. Table I summarizes the results of this experiment.

Optical tests of coherence, as we described, were made by passing the combined signal and local oscillator beams through an adjustable iris. Fig. 4 compares the coherence performance for one and for eight round trips through the line. The results agree with those of the other tests in indicating no measurable loss of coherence resulting from the additional 14 reflections. Within the accuracy of measurement it appears that the external optical components produce more beam distortion than the one-mile line.

3.3 *Four-Mile Line Configuration*

The round trips through the line were increased by two optical circulators to 32 (63 reflections) for a total length of four miles. Figure 5 shows the experimental setup. Light from the signal laser was first circularly polarized by a quarter-wave plate and then transmitted through a KDP rod where it was modulated at 84 KHz. One component of the modulator output was transmitted through the first analyzer prism, the other absorbed.

Table I —One-Mile-Line

Path (round trips)	Indicated Detection Efficiency (%)			Indicated line Loss (dB)	
	C/N	Beat	Variable Iris	Heterodyne	Direct Det.
1	81	98	100	—	—
8	81	87	112	0.9	0.95

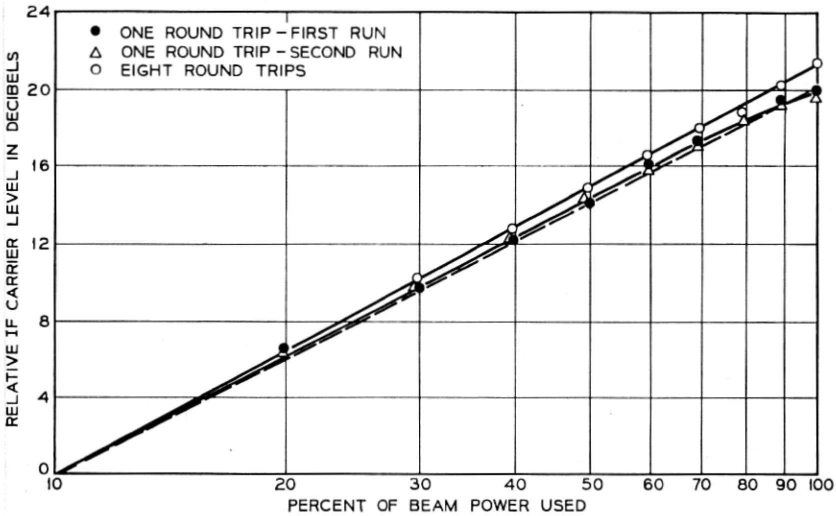

Fig. 4 — Phase coherence test comparing one and eight round trips.

The field of the Faraday-rotation isolator was adjusted to produce a 45° rotation of the plane of polarization of the amplitude-modulated output of the prism. A second analyzer prism, at the output of the isolator, was set to pass this polarization into the line. A quarter-wave plate in the line converted the input to circular polarization. After traversing the line for eight round trips the beam was reflected directly back on itself and returned to the quarter-wave plate. It emerged from the plate linearly polarized in a plane normal to that at which it first entered the line.

Analyzer prism 2 now directed this beam out of one of its side ports where a flat mirror reflected the beam directly back on itself and thereby launched it into the line for a second time. After 16 more round trips through the line the beam returned again to the quarter-wave plate. Upon emerging from the plate this time it had been restored to its original polarization and so was transmitted directly through prism 2 into the isolator. The additional 45° rotation imparted by the isolator caused its plane of polarization to be 90° from that of the original transmission. Upon leaving a side arm of analyzer prism 1, the beam was directed to the heterodyne receiver by a flat mirror and two beam splitters. One beam from the first beam splitter was applied to a photomultiplier direct detector where the 84 KHz modulation was recovered. The other was combined

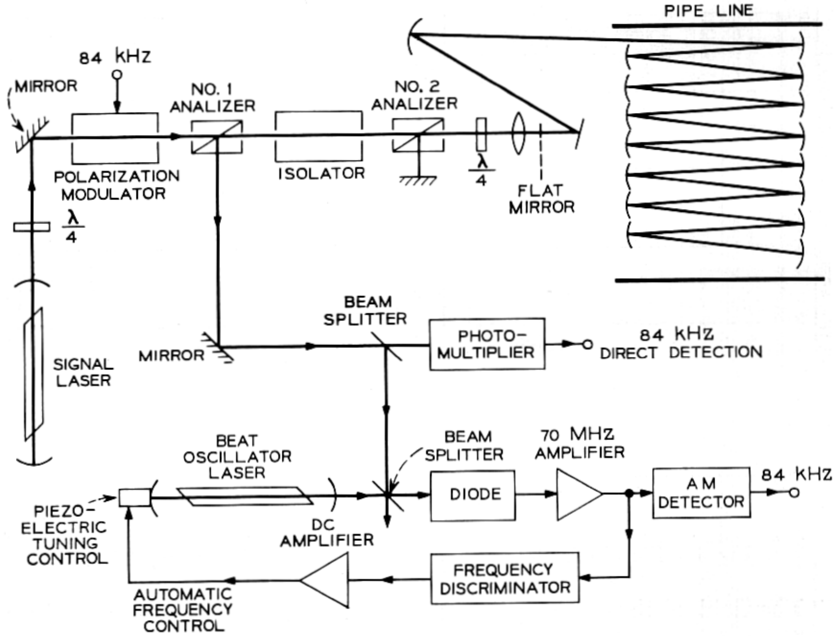

Fig. 5 — Experimental arrangements, four-mile path.

with the output of the local oscillator and applied to a photodiode detector. The 70 MHz output of the photodiode was amplified and detected by an electronic detector to recover the 84 KHz modulation.

The arrangement shown in Fig. 5 made it simple to determine the losses introduced by the four-mile line. By placing a flat mirror, shown dashed, at the focal point of the lens, light was caused to traverse the circulators and other components in the usual manner but transmission through the line was eliminated. Thus the line loss was the difference between the loss when light passed into the line and the loss when the line was blocked by the flat mirror.

To determine the effects of local optical components, the absolute detection efficiency was determined with only these components in the transmission path, that is, with the line blocked by the flat mirror. The average of a number of C/N measurements indicated a detection efficiency of 86 per cent. The beat method indicated 93 per cent.

3.4 *Four-Mile-Line Losses*

Table II summarizes the results of this experiment. The efficiencies and line losses that the table shows are averages obtained from a number of measurements. Fig. 6 shows the variable-iris data. Adding the line decreased the detection efficiency from 86 to 78 per cent, as indicated by the change of C/N. This is consistent with the line loss measurements and with the variable-iris check of coherence. The two curves of Fig. 6 show some loss of coherence after transmission over the longer path.

From the results of these experiments one might conclude that the four-mile line losses for a heterodyne receiver were about one decibel greater than for a direct detector. However, our measurements were not accurate enough to make this a reliable figure. It is likely to be somewhat pessimistic. In any case, it appears that heterodyne detection efficiencies near 80 per cent are obtainable even with light signals which have been transmitted through this long and complicated optical system.

We used no really elaborate beam-alignment or beam forming procedures for these experiments. We made the signal beam approximately plane-parallel by means of a telescope. The local oscillator beam remained slightly divergent, just as it emerged from the laser. Beam positions and angles were simply adjusted to produce maximum IF output from the detector. Although most of the optical components were stock items, the mirrors were rated good to 1/50 wavelength by the manufacturers, Laboratory Optical Co.

IV. STABILITY

Once it is determined possible to operate a light heterodyne receiver at the end of a long transmission line efficiently, the next question is whether this efficiency can be maintained for long. Our experiments indicate that, with reasonable care, it can.

There are two types of instability which can cause the system to malfunction: frequency variation and beam wander resulting from

TABLE II —Four-Mile-Line

Path	Indicated Detection efficiency (%)			Indicated line Loss (dB)	
	C/N	Beat	Variable Iris	Heterodyne	Direct Det.
Local Components Only	86	93	100	—	—
Local Components Plus 4-Mile Line	78		87	7.5	6.6

mirror tilt. Rough temperature compensation in the laser cavities was sufficient to keep our transmitting oscillator operating near the center of its doppler line. Automatic frequency control kept the average frequency of the local oscillator differing from that of the receiver by 70 MHz. The control voltage for this AFC came from a frequency discriminator operating at the intermediate frequency. Acoustical vibrations acting on the two lasers produced rapid deviations of the intermediate frequency obtained from the detector. These deviations, with peak values of a few megahertz, were passed without loss by the IF amplifier which had a bandwidth of 20 MHz. We have since practically eliminated these frequency shifts by using a different type mirror mount in the laser cavities.

Because all of our components were mounted on high temperature coefficient materials such as aluminum, brass, and steel there were some deviations in the position of the transmitted and received beams resulting from tilts produced by temperature variations. Our line, which was made up of single mirrors, was very much less stable than a practical line, which would have lenses or pairs of mirrors. Also, our experimental line was probably subjected to greater temperature changes than an underground line would be.[4] In any case it is evident that some form of beam position servo control will be necessary in a long transmission line.

4.1 *One-Mile Line*

For this experiment both transmitting and receiving equipment were mounted on the same steel plate at one end of the line. The steel

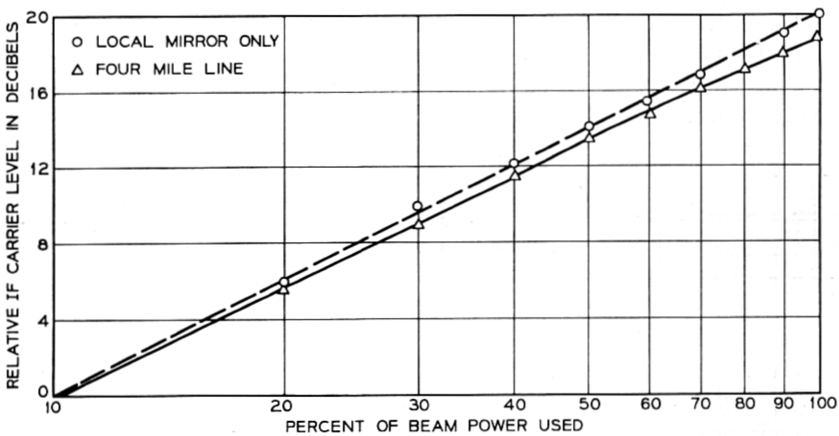

Fig. 6 — Phase coherence test comparing local and four-mile paths.

plate was on a wooden table which stood on a concerete floor. The presence of active components, such as the lasers, on this plate resulted in rather large point-to-point differences in temperature. As a result, this plate was the most unstable part of the transmission path and, if uncontrolled, the beam received at the far end of the path wandered about, sometimes going off the receiving mirror.

To stabilize the projected beam, four light sensors were installed behind the first mirror at the far end of the line. These sensors gave error signals which were amplified and applied to piezoelectric cylinders which in turn controlled the tilt of one of the launching mirrors. See Fig. 2. This system improved stability considerably.

A similar servo system was set up to control the position of the received beam to assure proper alignment of signal and local oscillator beams. The sensors were at the exit port of the line and the error voltages controlled the tilt of the last mirror at the far end of the line. With such an arrangement it should be possible to maintain the position of the received beam within a few thousandths of an inch—a fraction of a second of arc in our line. The remaining mirrors in the line had electrical tilt controls but these were all adjusted manually.

We connected a number of monitors to the system to study its stability. The outputs of these monitors were continuously recorded. Some of the quantities recorded were: (*i*) Vertical and horizontal error voltages from the output beam sensors. These voltages indicated the position of the received beam. (*ii*) The 84-KHz signal recovered by the heterodyne receiver. This indicated any fading of heterodyne signal which might have resulted from such factors as beam wander. (*iii*). The 84-KHz signal recovered from the direct detector. By comparing (*ii*) and (*iii*) we can measure any excess loss resulting from decrease of detection efficiency in the heterodyne receiver. (*iv*) Transmitted signal power. (*v*) Local oscillator power. (*vi*) Automatic frequency control error voltage.

From the recordings and from direct observation it was evident that the heterodyne receiver was noticeably less stable than the direct detector. However, the fluctuations of output of the coherent detector were usually less than ± 0.5 dB and occurred at low rates which could easily be removed by an AGC circuit. We should emphasize that the heterodyne detector diode was only 0.01 inch in diameter whereas the direct detector cathode was over an inch in diameter and could accommodate more movement of the received beam. Except for the small fluctuations just mentioned, the heterodyne receiver operated as well as the direct detector. The link operated all day, and at times for several days, without any readjustment and without serious loss of signal. Most times when signal loss did occur it was the result of detuning. A better AFC circuit should take care of this.

The charts in Fig. 7 indicate the stability during a typical six-hour period. The important consideration here is the comparison between the signals recovered by the direct detector and by the heterodyne receiver. Both follow the same general trend and both are completely free of any serious fades.

At point A, near the end of the chart, the servo loop which controlled the position of the final signal beam was opened. As a result, the beam position shifted enough to produce a 1 dB drop in the signal

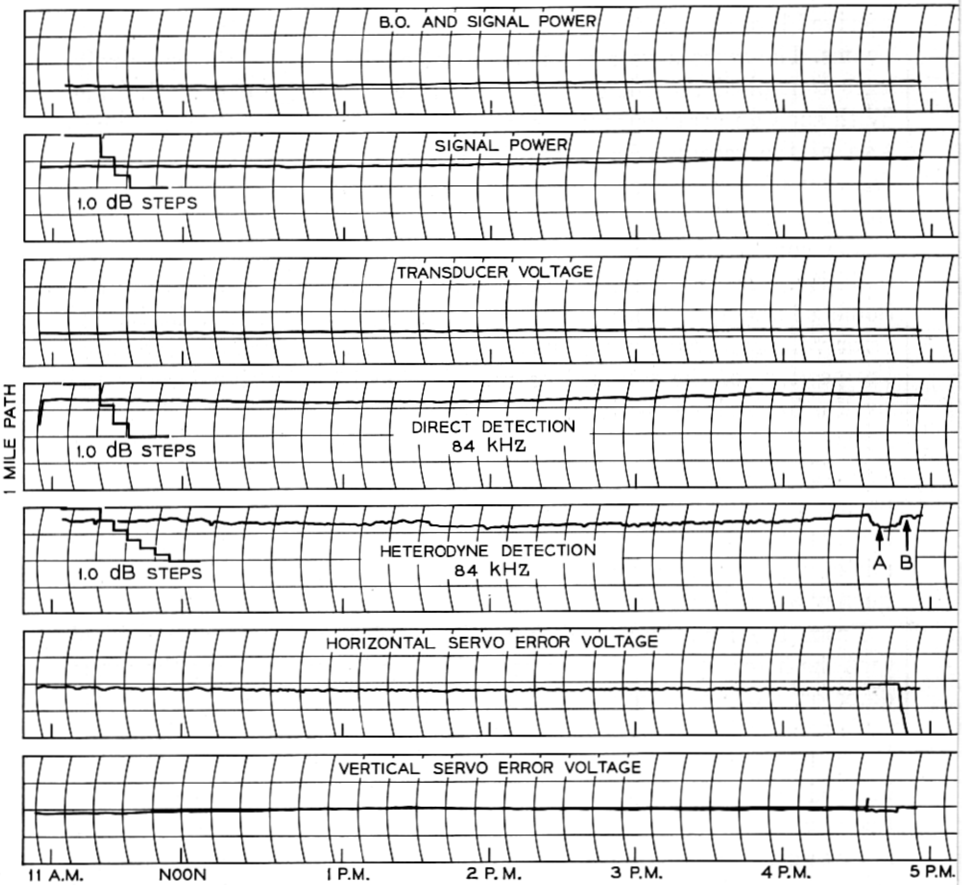

Fig. 7 — Signal received over the one-mile path.

from the heterodyne receiver. The output of the direct detector changed much less. At point B, the servo control had been restored and the signals returned to their former levels.

That the servo control system can be simple is evident from Fig. 8 which shows schematically the control circuit for one coordinate of one mirror. The components consist of two photoconductor cells, two vacuum tubes and two piezoelectric cylinders. The power requirements are 300 volts at a few milliamperes. With the vacuum tube amplifier it would also be necessary to supply heater power. When field-effect transistors capable of handling 300 V become available it should be possible to substitute them for the vacuum tubes.

4.2 *Four-Mile Line*

Because of the signal reflexing necessary for this experiment it was not possible to control the beam position by servo systems. In spite of this the configuration was quite stable. Fluctuations of signal level from the heterodyne receiver were only slightly greater than for the one-mile transmission but were considerably more rapid. These fluctuations, which had periods of several seconds, appeared to result from reflection of energy from the line back into the laser.

The isolator, supplied by C. B. Rubinstein of Bell Laboratories provided 40 dB of isolation. But because of resonances at very high

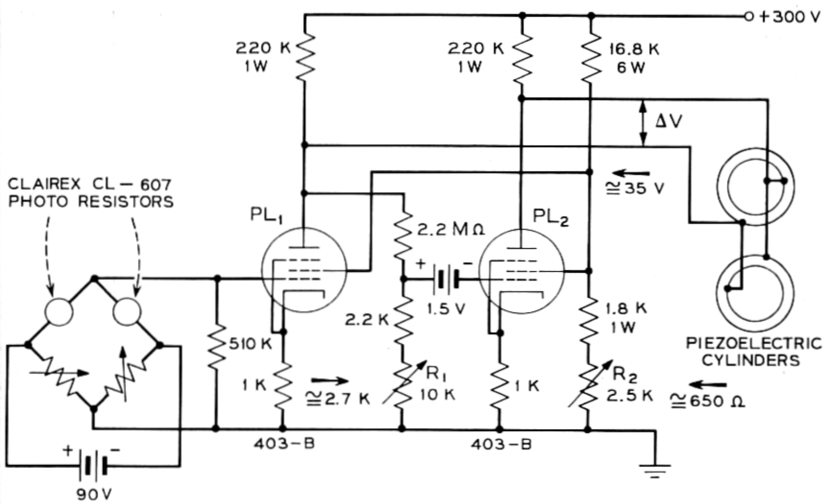

Fig. 8 — Automatic beam positioning control equipment.

Q the light power could build up in the line, and 40 dB apparently was not enough. Tests indicated that these fluctuations resulted from very small changes of length of the transmission path. When part of the path was through open air where the beam could be affected by air currents the fluctuations were considerably greater.

The charts in Fig. 9 show typical performance of the four-mile path for eight hours. The output of the heterodyne receiver decreased about 1 dB during this time. At the same time the output of the direct detector increased almost 1 dB as a result of increased power from the transmitting laser. This would indicate that the heterodyne receiver faded by almost 2 dB during this interval. If servo control of beam position had been possible it probably would have prevented this signal loss.

We do not wish to give the impression that the stability and reliability of our experimental setup did more than approach that required for a practical operating system. However, our observations lead us to believe that the required stability can be attained at reasonable expense by well known methods. To begin with, a practical line would have lenses or pairs of mirrors as beam directors which are much less sensitive to mechanical displacement than the single mirrors of our line. The practical line would also be underground where it would be much less subject to temperature variations.[4] Having the beam-director mounts made of low-temperature-coefficient material would help a great deal. Temperature control of the director environment could add stability but should not be necessary if beam position is controlled by servos.

Temperature control of the transmitting and local-oscillator lasers, along with the best AFC circuit should solve the frequency stability problem. Laser tube life would need to be extended.

V. CONCLUSIONS

We found that reduction in received signal caused by loss of coherence which resulted from transmission through a complicated system (including as many as 70 reflections) was small, comparable with the measuring errors. The losses in a four-mile transmission path, as measured by a heterodyne receiver, were about 1 dB greater than the losses in the same path measured by a direct detector.

We also found that even without complicated controls the system was sufficiently stable to maintain near-optimum operation for fairly long periods of time. However, our observations indicate that for long-

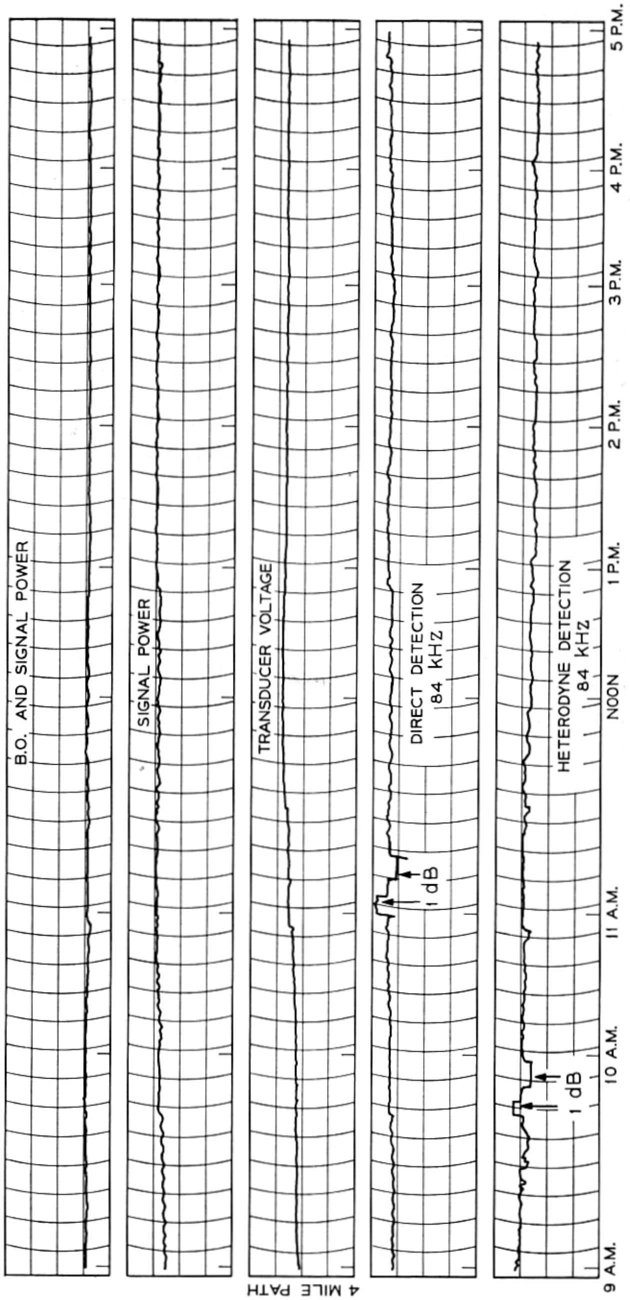

Fig. 9 — Signal received over the four-mile path.

distance systems which must operate for extended periods with great reliability it would be necessary to use more sophisticated control circuits. Stability, aside from frequency control, is simply a matter of proper beam alignment. This alignment is necessary to obtain reliable transmission through the line so that the heterodyne receiver requirements are little more severe than the requirements for any other type of receiver.

Although most likely there would be some improvement in efficiency through using better optical components, the stock components that we used gave quite satisfactory performance.

It is interesting that even though it is visually evident that the mirrors we used had deteriorated and accumulated dust over a period of years, the line loss measured now is 0.85 dB per mile in comparison with an average of 0.9 dB per mile measured by a different method when the mirrors were new. That is, any change of line loss is less than the error of measurement.

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