✓
8-17-77

UCRL-13754

REPORT NO. P77-304
HAC REF D6062

TECHNICAL MANUAL
(Contract No. 9660315)

PULSE SYNCHRONIZATION SYSTEM (PSS)

WORK PERFORMED UNDER CONTRACT TO
LAWRENCE LIVERMORE LABORATORIES

P.O. 9660315

JUNE 1977

AEROSPACE GROUPS

HUGHES

HUGHES AIRCRAFT COMPANY
CULVER CITY, CALIFORNIA

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

PULSE SYNCHRONIZATION SYSTEM (PSS)

Contract No. 9660315

Work Performed Under Contract to
Lawrence Livermore Laboratories

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

June 1977

Electro-Optical and Data Systems Group
Laser Division
AEROSPACE GROUPS
Hughes Aircraft Company • Culver City, California

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

EP

CONTENTS

1.0	INTRODUCTION AND SUMMARY	1
2.0	SYSTEM DESCRIPTION	3
2.1	Description - Optical Layout (Figure 2-1)	3
2.2	Pulse Synchronization System Description - Signal Processing (Figure 2-2)	5
2.3	System Photographs	7
3.0	SYSTEM ALIGNMENT AND OPERATION	11
3.1	System Alignment	11
3.2	System Operation	16
4.0	PHYSICAL DESCRIPTION	23
4.1	Description - Circuit Board A1 (Figure 4-1)	23
4.2	Description - Circuit Board A2 (Figure 4-2)	25
4.3	Description - Circuit Board A3 (Figure 4-3)	27
4.4	Description - Circuit Board A4 (Figure 4-4)	29
4.5	Description - Circuit Board A5 (Figure 4-5)	31
4.6	Description - Circuit Board A6 (Figure 4-6)	33
4.7	Description - Circuit Board A7 (Figure 4-7)	35
4.8	Description - Circuit Board A8 (Figure 4-8)	37
4.9	Description - Circuit Board A9 (Figure 4-9)	39
4.10	Description - Blast Shutter and Intracavity Shutter Operation (Figure 4-10)	41
4.11	Description - Chopper Reference Signal Circuit (Figure 4-11)	42
4.12	Description - Laser Hookup and Operation (Figure 4-12) ..	43
4.13	Description - Detectors and Preamplifier (Figure 4-13) ..	46
4.14	Electronics Control Panel (Figure 4-14)	47

CONTENTS (Continued)

5.0	SUPPORTING CALCULATIONS	51
5.1	Characterization of the Signals	51
5.2	The Carrier Signal to Noise Ratio (SNR_c)	54
5.3	The Double LO Technique for Position Measurement.....	57
5.4	LO Beamsplitter Analysis	61
5.5	Effects of Aberrations on SNR	64
5.6	Ghost Signals	67
5.7	System Performance Estimate	73
5.8	Appendix Calculation of Degradation in SNR_m Due to Envelope Detection	77

LIST OF ILLUSTRATIONS

Figure		Page
1-1	Waveform Relationships	2
2-1	Optical Layout	4
2-2	Electronics - Signal Processing Diagram	6
3-1	Dual LO Alignment Detector Preamplifier Outputs for Detector Motions	17
3-2	IF Signal Waveforms	18
4-1	Electronics - Circuit Board A1 - Shutter Control	24
4-2	Electronics - Circuit Board A2 - Post Tuned Filter,	26
4-3	Electronics - Circuit Board A3 - Boost Amplifier and Envelope Detector	28
4-4	Electronics - Circuit Board A4 - Pre-Filter	30
4-5	Electronics - Circuit Board A5 - Dither Oscillator	32
4-6	Electronics - Circuit Board A6 - Dither Drive	34
4-7	Electronics - Circuit Board A7 - +50 VDC, +24 VDC, +15 VDC Supply	36
4-8	Electronics - Circuit Board A8 - Dual ± 15 VDC Supply	38
4-9	Electronics - Circuit Board A9 - Dual +24 VDC Supply	40
4-10	Electronics - Optical Table - Shutter Systems Box	41
4-11	Electronics - Optical Table - Chopper Reference Signal Circuit	42
4-12	Laser Hookup and Operation	44
4-13	Electronics - Optical Table - Detectors and Preamplifier	46
4-14	Electronics Control Panel	49
5-1	Variation of Signal Current with Path Length Difference	58

ILLUSTRATIONS (Continued)

Figure		Page
5-2	Dependence of SNR on the Ratio $\Delta/2$	60
5-3	LO Beamsplitter Configuration	61
5-4	Geometry of a Specular Reflection	68
5-5	Degradation Factor	75
5-6	Estimated Position Error Versus Signal Path Transmission	76

1.0 INTRODUCTION AND SUMMARY

The following pages are intended to serve both as an operations manual, as well as a documentation of the backup analyses pertinent to the design as delivered. A history of earlier unsuccessful versions of the Pulse Synchronization System (PSS) is not included because of the lack of relevance to the present system and the delay that would be incurred in the delivery of this technical manual.

The function of the PSS is to synchronize the time of arrival at the fusion target of laser pulses that are propagated through the 20 amplifier chains of the SHIVA laser. The positional accuracy requirement is ± 1.5 mm (± 5 psec), and is obtained by the PSS with a wide margin factor. The principle of operation is illustrated in Figure 1-1. The PSS NdYAG laser injects a CW mode locked pulse train into the SHIVA oscillator chain. Nineteen of the amplifier chains are shuttered out, and the PSS pulse train is allowed to propagate down the selected amplifier chain to a reflective sphere placed at the focus of the last lens. The reflected beam returns to the PSS and is heterodyned with a frequency shifted portion of the laser output. The amplitude of the beat frequency current depends on the relative optical path lengths of the local oscillator (LO) path and the signal path. The method by which this behavior is exploited to obtain the required position accuracy is illustrated in Figure 1-1b. A chopper directs the LO beam alternately through two different LO optical path lengths: LO_1 (the dashed response curve), and LO_2 (the solid response curve). A phase lock amplifier with the chopper as a reference then detects the difference of these two curves yielding a meter reading that varies with the optical path difference X as shown in Figure 1-1c. If X is adjusted to the central null, then the

Figure 1-1. Waveform relationships.

meter will remain nulled as the signal strength varies; consequently, when each amplifier chain is successively switched in and its optical path length adjusted to give a meter null, the path lengths will be synchronized independent of variations in signal strength.

Theoretical performance estimates are summarized in Figure 5-5. These estimates are approximately verified when the PSS is tested by itself. When working into the CYCLOPS laser, the PSS was found (6/17/77) to be disturbed by deep fading which appeared to be related to the time varying turbulent distortions observed on the PFC camera. The CYCLOPS attenuation was augmented to a total of 90 dB and the meter observed to go through a null upon translation of the LO cat's eye; however, the resolution was considerably worse than ± 1.5 mm. A clarification of this noise mechanism may be obtained through experiments (6/21/77) currently underway at Livermore.

2.0 SYSTEM DESCRIPTION

2.1 DESCRIPTION - OPTICAL LAYOUT (FIGURE 2-1)

The modelocked output of the Quantronix laser is monitored through the rear mirror. Although pulsewidths of less than 150 picosec are possible by careful alignment, a 250 picosec $1/e$ width pulse will be utilized. This is necessary to minimize the drift in the lockin meter reading caused by spurious periods of relaxation oscillations of the laser. Greater stability and quiet operation are obtained by allowing the pulsewidth to grow. This stabilization has been effected by addition of a 1 mm etalon.

The beam is expanded to 4 mm and collimated by a 4X beam expander. The laser output, due to thermal birefringence, is not unipolar and a good polarizer is added externally. The beam passes through a half wave plate. Rotation of this plate allows control of the energy in the polarization selected by the polarizing beamsplitter to be the LO beam. The beam is split by the beamsplitter into the signal and local oscillator (LO) beams.

The signal beam traverses a quarterwave plate and exits circularly polarized. The laser chain polarization device selects one polarization. The attenuated return signal beam (-90 dB) passes again through this quarter waveplate and is circularly polarized. The polarizing beamsplitter puts a component into the detection arm. The beam is folded and enters a Wollaston prism inclined at 45 degrees relative to the signal polarization. The signal is thus divided and impinges on the two detectors.

The LO beam is folded upon leaving the beamsplitter. It then passes through the "dual LO oscillator device." The beam is equally split into two beams which are spatially separated. A chopping blade alternately selects one and then the other of these dual beams. In the figure, it is seen that the

Figure 2-1. Optical layout.

upper beam travels a farther distance while passing through the device. This provides the two LO beams with differing path lengths. The beams (if both were allowed to pass) recombine and enter the dithering retro. The combination of quarter waveplate and specular reflection off of the rear retro surface rotate the LO polarization by 90 degrees. The retro is translating back and forth along the optical axis. This phase modulation of the beam provides the heterodyne frequency offset. The beam is retro-reflected and shifted in frequency. It makes a second pass through the dual device doubling the path length difference. Since it is now rotated in polarization, it passes through the polarizing beamsplitter into the detection arm. It is polarized at right angles to the signal polarization and is split by the Wollaston and placed onto both detectors. The heterodyne beat is detected by both detectors. Due to the quadrature polarization the beat signals are out of phase by 180 degrees, and when differenced, add. Noise, or self beats of either the signal or local oscillator beams are in phase and when differenced are attenuated (Ideally canceled). The resulting differenced signal then enters the electronics for signal processing.

2.2 PULSE SYNCHRONIZATION SYSTEM DESCRIPTION - SIGNAL PROCESSING (FIGURE 2-2)

A heterodyne signal between the local oscillator and signal returns is detected by both detectors. This detected heterodyne frequency offset signal is time varying. It is actually the detected phase modulation of the LO beam imparted by the dither motion. Its amplitude depends on the relative path length difference between the LO and signal optical paths. The balanced detection system reduces noise components, and chopping transients. Since the LO beam can travel along two differing paths, a square wave amplitude modulation results on the detected heterodyne signal. The modulation index depends on the relative path length difference between the median LO path and signal path. It approaches zero when the median path and signal path length difference is an integral number of laser resonator round trip cavity lengths. It is this null or zero that is detected by the lockin amplifier, that indicates path length equalization.

Figure 2-2. Electronics - signal processing diagram.

The detected beat signal is first current mode differenced (balanced detection) and then preamplified. Although a large LO noise rejection is achieved by the balanced detection, chopping noise transients are ~80 dB above the detected signal. A prefilter is added and in conjunction with the balanced detection gives rejection providing the necessary attenuation of these transients.

The prefilter is required for two reasons: 1) the following large amplification stages would be saturated by the large chopping waveforms, and 2) the envelope of the carrier becomes ambiguous at the dither mirror turnaround and must be attenuated. The prefilter employs 4 stages of 3rd order highpass filters. A small price is paid since the heterodyne signal is varying from near zero frequency to 100 kHz. This highpass filter causes a modulation of the detected waveform at twice the dither rate. Since the LO chop frequency is significantly higher, the result is only a loss in average signal as recorded by the lockin amplifier.

Following the prefilter, the signal level is boosted to 1 volts peak to peak for use in a diode envelope detector. Two amplifiers with switch settable gains of one (1) and ten (10) and one hundred (100) are followed by a

continuously variable stage of one (1) to one hundred (100). A boost in signal level of one (1) to five hundred thousand (500,000) is possible.

The signal is split and sent to two buffered envelope detectors. A large time constant on the meter detector provides a dc output to drive a signal level meter. This is calibrated to indicate the required 1 volt p-p signal. The second, shorter time constant detector demodulates the square wave AM modulation.

In order to increase the dynamic reserve of the lockin amplifier, a post tuned filter centered on the chopped LO frequency is utilized. This is a variable Q, variable frequency filter. It is set with the chopped frequency at center and a Q of 5-10. The signal is detected by the lockin amplifier providing a meter indication. A meter null indicates equalization (integral number of laser cavity lengths L).

2.3 SYSTEM PHOTOGRAPHS

The photographs included below serve to illustrate the delivered hardware, which includes:

1. Laser head and optical table
2. Laser power supply
3. Laser mode locker
4. Spectra physics detector and power supply
5. Spare optical and electronic parts (not shown)

The digital counter and the oscilloscope were not deliverable items.

3.0 SYSTEM ALIGNMENT AND OPERATION

3.1 SYSTEM ALIGNMENT

The Pulse Synchronization System is based upon the heterodyne detection of signals, and must therefore be carefully aligned and maintained. A detailed alignment procedure follows and must be explicitly followed each time. Although tweaking of a single component may appear to restore operation, the sensitivity and/or resolution may be severely affected.

Mode Locked Laser

The laser cavity is formed by a 1 meter radius of curvature rear mirror, and a front flat partially transmitting mirror. The front mirror is wedged to avoid etalon effects between surfaces. This wedge causes beam steering and a second s tellite beam. The rod exhibits thermal focusing and the cavity has been set up for operation from 18 to 24 amps lamp current. A nominal setting of 20 amps should be maintained. The AO cell is located between the rod and front mirror. A Brewster's stack polarizer, intracavity shutter, and 1 mm etalon are located between the rod and rear mirror. A mode limiting aperture is attached to the front mirror mount. IT IS IMPORTANT TO REMEMBER THAT ALL THESE COMPONENTS TILT OR TRANSLATE THE OUTPUT BEAM CHANGING SYSTEM ALIGNMENT. THEREFORE, THE LASER MUST BE ALIGNED, OPTIMIZED FOR MODELOCKED OPERATION AND THEN LEFT ALONE.

The laser should be aligned for maximum power output with the mode aperture open and AO cell set approximately for the Bragg angle. The mode aperture should be closed down and centered repeatedly for maximum power

using the provided tool. This will center the aperture. The etalon should be removed during this first alignment. Follow the Quantronix manual for adjustments of the polarizer, AO cell, and Bragg angle. The etalon should be inserted and adjusted for maximum output power. This is accomplished by using the required ball drive through the rear mirror and hole in the intracavity shutter enclosure.

The output pulse should now be monitored through the rear mirror using a 50 picosec risetime detector and sampling plug-ins. The modelocker should be set to 1.5 watts forward power by the adjustment screw on the rear panel of the driver box. Cable lengths may need to be varied to reduce the reflected power. The drive frequency and Bragg angle of the AO cell should be simultaneously adjusted for minimum pulsewidth. This should be approximately 250 picosec FWHM. Centering of the beam in the mode aperture, output power, etc. should be rechecked as movement of the AO cell causes beam translation. The pulsewidth appearance should be a smooth Gaussian curve. (Reducing the mode aperture causes a power reduction but provides this smoothing.) Changing the drive frequency should cause a slow broadening of pulse on either side. Secondary peaks or other anomalies indicate improper adjustment and alignment.

The modelocked output should now be stable with 250 picosec FWHM, with 500 m watt average power output with a lamp setting of 20 amps. The laser cover should be replaced and the laser left alone, except for occasional drive frequency adjustments.

Output Beam Collimation

The modelocked laser output passes through a four times (4X) beam expander. It exits at approximately a 4 mm diameter. This beam expander must be centered on the beam and the mount locked down. The objective lens moves back and forth within the barrel to achieve collimation. A locking ring must first be loosened. A very thin shearing plate is used to set collimation.

External Polarizer and Half-Wave Plate

The laser output is polarized by an internal Brewster's stack polarizer. However, the rod thermal birefringence destroys this across the beam diameter. An external polarizer is required to restore the polarization purity required. With the system polarizer, halfwave plate, and polarizing beamsplitter removed, a calibrated polarizer in a rotational mount is inserted into the beam and adjusted for best extinction. The extinction will not be complete, and will be best only at the center of the beam. The system polarizer is inserted in its mount and rotated until total extinction across the beam results. The laser output is now a clean vertical output polarization. The calibrated polarizer is rotated exactly 90 degrees. The half waveplate is inserted and adjusted to best extinction. The beam has been rotated by 90 degrees and is now horizontal. It will now pass through the output polarizing beamsplitter and become the signal beam. By turning this waveplate small amounts, a small vertical component is developed and it passes into the LO arm becoming the LO beam.

Polarizing Beamsplitter

The beam exiting the polarizer-waveplate fixture passes through a polarizing beamsplitter and its s and p components are split into the respective signal and LO arms. An auxiliary centering stop with outer dimension matching the beamsplitter face, and a hole or aperture matching the size of the beam, allows the beamsplitter vertical, and horizontal positions to be adjusted. The beamsplitter rotation about a vertical axis is adjusted to give maximum extinction in the LO path. Beam height is 8.0 inches. A tilt adjustment is also provided and is used to adjust the beam parallel to the table at 8.0 inches height. The auxiliary stop is repositioned to the LO side face to facilitate adjustment of the retro return.

LO Folding Mirror - Retro Tracking Adjustment

During system operation, the dithering retro assembly must track over 50 cm along the rail. The folding mirror and retro must be adjusted to provide this tracking. The dual beam assembly is removed from the rail and

chopper positioned for beam throughput. Increase the LO arm power by rotating the half waveplate, to facilitate alignment. Return to initial position when finished. The folding mirror is initially adjusted to provide a beam parallel to LO rail at a height of 8.0 inches (7.5 inches above rail top). An iris is closed on the front of the retro and beam observed with an IR viewer. Both the retro and folding mirror are adjusted to maintain this centered position as the retro assembly is translated back and forth along the rail. The iris is opened and the retro return adjusted to pass back through the cube beamsplitter target. Insure tracking. Observe the retro return on the detector side of the cube beamsplitter.

Insert the dual beam assembly back on the rail and adjust the flats for 45 degrees. It may be necessary to TRANSLATE the folding mirror and retro by equal amounts to offset the translation of the flats. Observe the two existing beams at the second surface of the first flat (chopper side). Adjust the folding mirror so that the two beams are equi distant from the optical coating line on this surface. Slight adjustments should be necessary. Adjust retro for tracking and return through cube target.

Detector Arm Folding Mirror

The LO beam is now in the detection arm. Adjust the folding mirror for a beam parallel to the detector rail at a height of 8.0 inches. Close down the iris in front of the detectors. Use a small aperture and align the detector assembly to the beam. Visually assure that the detector cylindrical body appears level and parallel to the beam. A large misalignment can result in reflections from the walls of the detector assembly that may appear to be in alignment.

Remove the two detectors from the mounts. Insert the two plexiglass targets with metal crosshairs. Adjust the detector assembly to center the observed beams on the crosshairs. The detector assembly is comprised of a focusing lens, Wollaston prism and two detectors. The Wollaston prism splits s and p polarizations and puts each on a detector. The angle between the beams is 5 degrees. Vertical, horizontal, and rotational adjustments are provided. In addition, the beam separation is adjusted by translating the

detectors towards or away from the Wollaston prism. Turning the rear knurled collar accomplishes this.

This completes the preliminary alignment. REMEMBER TO REMOVE THE DETECTOR TARGETS AND REPLACE DETECTORS.

Dual LO Alignment

This is the final alignment step. Unless those proceeding this have been carefully accomplished there is no reason to proceed. For successful heterodyne detection we must match phase fronts, beam size, and have colinear beams at the detector surfaces. As a further complication, this system has two separate LO beams, which must be simultaneously aligned with the same signal beam. The following procedure must be followed to accomplish this.

The preamp monitor output on the electronics panel should be connected to an oscilloscope. The chopper reference should be used as an external trigger. Turn on the chopper (switch on the black box in close proximity). If the preceding alignment was followed, a chopped signal waveform should be seen on the oscilloscope. Using a piece of folded paper, block one of the LO beams. A chopped waveform should still be observed. There are three adjustments to the detector assembly that will be required. These are tilt about the horizontal, rotation about the vertical, and rotation of the whole detector body about the beam axis. Rotate the body about the beam to effect a quasi straight line display. Tilt about the horizontal, first one way and then the other. The chopper waveform will return, first above, then below zero. We wish to achieve symmetry of these excursions above and below. Small rotations of the body will eventually achieve the desired symmetry. Repeat for rotation about vertical. Continue until both tilt about horizontal and rotation about vertical, both + and -, achieve the desired symmetrical excursions, with a straight line display at middle settings. This has aligned one LO beam to the detectors and balanced their amplitudes.

Unblock the second LO beam. The only adjustments are made to the beam splitting flats. Only very minor adjustments are required. By adjusting the flats about vertical and 45 degrees we are aligning the second LO beam to

the first. It is essential that they do coincide. Carefully, with small adjustments restore a straight line display. (Unblocking second LO beam should result in a chopped waveform on the scope).

We have now aligned the two LO beams to the detectors and each other. The last alignment item is adjustment of the chopper. The chopper alternately blocks one or the other of the LO beams. However, there are transitional regions where both beams exist. (One coming on, one going off). It is necessary to adjust the duty cycle of the chopper to less than 50 percent. The dual blades allow variable spacings. The spacing is empirically adjusted to remove the transitional periods. Symmetrical waveform is set by the height adjustment on the chopper. Horizontal adjustment has little or no effect. This completes the system alignment. The remaining adjustments are operational. Figure 3-1 shows the sketches of the various waveforms desired.

3.2 SYSTEM OPERATION

Once, stable modelocked laser operation has been achieved, and a careful alignment performed, the system is ready for operation. A brief review of the theory, and usage is required to provide direction for the following operational adjustments.

The modelocked pulse train is amplitude divided and the signal portion transverses the amplifier train, is retro-reflected, and returns. It suffers attenuation and a time delay. It is heterodyne detected with a LO pulse train that has been shifted in frequency by the motion of the dithering retro mirror. Only when the pulse trains overlap is there a detected signal. This positional overlapping creates a heterodyne response curve for each LO beam. Since there are two LO pulse trains, themselves having a relative delay, a response curve like that shown in Figure 3-2 results. IT IS IMPORTANT TO REALIZE THAT A CHANGE IN THE MODE SPACING OF THE MODES SUMMING TO THESE PULSE TRAINS SHIFTS THESE CURVES. IT IS THEREFORE, IMPERATIVE THAT THE MODELOCK DRIVER NOT BE ADJUSTED DURING A MEASUREMENT. The chopper alternately selects one LO beam then the other. This results in a square wave amplitude modulation of the detected heterodyne signal. Refer again to Figure 3-2. It can be seen that for a fixed

REQUIRE EQUAL MAXIMUM EXCURSIONS
FOR MOTIONS ABOUT AXES - EQUALIZE
EXCURSIONS BY ROTATION OF THE DETECTOR
BODY ABOUT THE OPTICAL AXIS

Figure 3-1. Dual LO alignment detector preamplifier outputs for detector motions.

HETERODYNE RESPONSE CURVES

PATH LENGTH DIFFERENCE $< NL$
($N = \text{INTEGER}$)

PATH LENGTH DIFFERENCE $= NL$

PATH LENGTH DIFFERENCE $> NL$

Figure 3-2. IF signal waveforms.

relative LO spacing, when the relative path length x (see Fig. 1-1) is an integral number of cavity lengths, the square wave modulation has a null. Moving off center causes one LO response to increase and the other to decrease, and vice versa for a movement off center in the other direction. Therefore not only is the magnitude of the equalization offset indicated, but also its direction with respect to the ref arm is indicated.

Initial Test for Operation

Before using the PSS on the laser amplifier chains, a bench test should be performed to insure optimum performance. -90 dB attenuation. Measure the distance from the center of the polarizing beamsplitter along the folded optical path to the rear of the dither assembly. Set up a flat gold mirror at one or two times this distance. Place a filter holder and ND filters about a foot from the signal exit aperture of the pulse synchronization system. Tilt these filters so that any Fresnel reflections strike the front panel and do not re-enter the system. Starting with ND of 2 (-40 dB round trip), adjust the flat return mirror for a heterodyne return. This can be observed on the preamp output or boost amp output and will be a very large signal. Periodically block the signal path to insure a signal is present. With the signal blocked, increase LO power by rotating the half waveplate, until the waveform on the boost amp output exhibits noise spikes on the waveform during transitional periods of the chopper. See Figure 3-1. Gradually increase the ND to a total of 4.5. At this attenuation a signal to noise of 5 or less with a p-p value of 1 volt should be present. Each time a new ND filter is added maximize the signal by tweaking the flat return mirror. Optimize the signal by rotating the output quarter waveplate.

At this point, the resolution is ready to be tested. When the alignment, LO power, and signal return have been optimized, block the signal beam, and adjust the front panel boost amp control while monitoring the envelope detector output. Adjust it high so that the noise spikes can be seen and then gradually reduce the gain until the noise is thresholded.

Unblock the signal, and the square wave output of the envelope detector should be seen. Ensure that the post amp is tuned to ref chopper frequency.

See discussion of electronics. The PAR lockin should be turned on, and allowed to lock on to the chopped frequency. Adjust the amplitude and time constant to get a response. Displace the dither assembly so that a visible square wave is seen modulating the boost amp output. Using the lockin phase settings obtain a null on the meter. Now turn the phase switch by 90 degrees and move the dither retro assembly to obtain a null. The PAR now has been calibrated. The reference phase adjustment need not be touched again. Lock down the front part of the dither assembly and adjust the micrometer two two full turns (1 mm). A meter deflection of 0.4 to 0.8 units should occur (for an attenuation of 10^9). Experience in alignment and operation of the system will be required to obtain the near full scale deflection.

Nominal Settings

PAR Input A
 Input Level - 25 mV
 Input Filter - Switches in Center Position
 Time Constant - 3 sec
 Other Functions - Out or Off

Electronics Panel

Dither - On - 1.0 setting
Boost Amp - 0 - 1.0 setting
Level - 9.5 Setting
Q - 6.0
Frequency - Center Position (Adjust for Optimum)

Operational Usage

Testing on the Cyclops chain showed that basically there is no difference in operation of the system. The laser power was visible on the alignment camera at the target. The output quarter waveplate was rotated for maximum observed intensity as indicated on the TV camera monitor.

Ghost signals, or retro reflected returns from certain elements up to the first rod amplifiers must be carefully watched. In the Cyclops system many flat surfaces such a corner cubes front face, plano convex lens, proved to be a problem. These were quickly eliminated by slight adjustments to

these components. Additionally beam splitters and partially transmitting mirrors caused some problems with the transmitted beams striking mounts etc. and back scattering. Replacement with gold front surfaces mirrors eliminated these false returns.

Operation was the same as the bench test. Once a signal is detected and optimized, set the boost amp level to threshold the background noise. The system is now operational and the first amplifier chain has been set up as the reference. By going to successive arms the meter will deflect + or - indicating which way the path must be changed. The path length equalizers are positioned to obtain a meter null on the PAR. This path is now within a fraction of a millimeter to the reference arm. Although not necessary, it would be good measurement practice to periodically check the reference channel for a null. Proceed with each chain, one at a time, obtaining nulls on the meter. NO CHANGES TO ANY FUNCTION OF THE PULSE SYNCHRONIZATION SYSTEM SHOULD BE MADE DURING MEASUREMENT. ONLY THE ACTUAL PHYSICAL PATH LENGTH OF THE CHAIN BEING MEASURED SHOULD BE EFFECTED. Failure to do so changes the calibration of the reference and it must again be nulled as described above.

4.0 PHYSICAL DESCRIPTION

4.1 DESCRIPTION - CIRCUIT BOARD A1 (FIGURE 4-1)

Circuit board A1 contains switching transistors to control current through the windings of the blast and intra cavity shutter relays. Two identical circuits are provided, one for each shutter. Base drive is provided by a manual switch on the front panel. When this switch is closed, base current flows, turning on the transistor and illuminating the LED indicator. This causes current to flow in the relay windings pulling down their switch contacts. This in turn energizes the shutter, opening it. Additionally, a status light goes from green to red. External control is provided to shut the shutters, for instance during a chain firing pulse. An external short or low impedance removes the base drive current turning off the LED indicator and transistor de-energizing the relay and shutter, which then closes.

a.

b.

Figure 4-1. Electronics - Circuit Board A1 - Shutter Control.

4.2 DESCRIPTION - CIRCUIT BOARD A2 (FIGURE 4-2)

Circuit board A2 is the post filter. It is the final filter centered at the chopped LO frequency, to increase the dynamic reserve of the lockin amplifier. It is frequency tunable, and its Q (bandwidth) can be varied. Frequency tuning is provided by the two ganged potentiometers, and Q is varied by the potentiometer in the overall feedback loop. Normal operational settings are center scale on frequency and a 6.0 setting on Q. By feeding the reference signal into the envelope detector monitor using a 100-1 attenuation, the frequency can be optimized by a maximum meter deflection on the lockin amplifier meter.

4.3 DESCRIPTION - CIRCUIT BOARD A3 (FIGURE 4-3)

Circuit board A3 contains three functions. These are the boost amplifier, the signal level monitor circuit, and the AM demodulator or envelope detector.

The boost amplifier contains three (3) amplifying stages. The first two amplifiers can be set at gains of one (1), ten (10), fifty (50), and one hundred (100) with a switch assembly. A closed condition is synonymous with on. The third stage is continuously variable by a potentiometer located on the front panel.

The signal is split and isolated by buffering stages. A long time constant envelope detector followed by a unity gain buffer drive a signal level output meter. The variable adjustment is for calibration of the meter to indicate half scale when 1.0 volts p-p signal is present.

A short time constant envelope detector follows the heterodyne detected signal, amplitude modulated envelope. This demodulated output passes through a potentiometer. This pot controls the signal level into the lockin amplifier and is adjusted to avoid an overload condition. It is located on the front panel.

The gain on the boost amp is used to maintain the noise below the forward conduction voltage of the envelope detector. In this manner the noise is thresholded. Any signal with S/N greater than 1 will then be received by the PAR. Normal operational settings are:

1. Boost Amp - 0.1
2. PAR Input Level - 9.5

Figure 4-3. Electronics - Circuit Board A3 - Boost Amplifier and Envelope detector.

4.4 DESCRIPTION - CIRCUIT BOARD A4 (FIGURE 4-4)

Circuit board A4 is designed to remove low frequency chopped LO components and transitional transients of the chopping blade. It is comprised of four (4) stages of active highpass filters. Each filter is a 3rd order active high pass filter with cutoff at 30 kHz. The overall four stage response is down -12 dB at 30 kHz, -70 dB at 10 kHz.

4.5 DESCRIPTION - CIRCUIT BOARD A5 (FIGURE 4-5)

Circuit board A5 is a switched sine or triangle function generator. Symmetry and waveform are fixed sinewave adjustments. Amplitude is controlled by the 50 K Ω pot, frequency by the 100 K Ω pot, and switched between sine and triangle operation by an on board switch. Actual operation will be either sine or triangle depending on which provides the best results. (Minimum turnaround time - low frequency periods.) The output is split, one serving as a constant reference signal at the front panel, the other goes to a front panel pot and on to the dither driver.

4.6 DESCRIPTION - CIRCUIT BOARD A6 (FIGURE 4-6)

Circuit board A6 is the dither driver. It receives a controlled drive signal from the front panel dither adjustment. It is a differential driver. A drive current monitoring circuit is not used. It is comprised of a commercial 6 watt dual audio range amplifier chip.

a.

b.

Figure 4-6. Electronics - Circuit Board A6 - Dither Drive.

4.7 DESCRIPTION - CIRCUIT BOARD A7 (FIGURE 4-7)

Circuit board A7 is a three voltage output supply. +15 regulated output drives the dither indicator light. +24V large current provides that required for the dither driver. The unregulated voltage is used to power the blast shutter solenoid.

a.

b.

Figure 4-7. Electronics - Circuit Board A7 - +50 VDC, +24 VDC, +15 VDC Supply.

4.8 DESCRIPTION - CIRCUIT BOARD A8 (FIGURE 4-8)

Circuit board A8 is a dual ± 15 regulated supply. Two commercial 24 VDC supplies are used to provide the ± 24 VDC input to the LM125 ± 15 tracking regulators. The output from one regulator powers the electronics while the other supplies bias for the detectors and preamplifier.

a.

b.

Figure 4-8. Electronics - Circuit Board A8 - Dual ± 15 VDC Supply.

4.9 DESCRIPTION - CIRCUIT BOARD A9 (FIGURE 4-9)

Circuit board A9 is a dual +24 VDC regulated supply. Commercial 28 VDC supplies are regulated to +24 VDC. One output supplies the electronics. The other provides power for the blast shutter relays and circuits.

a.

b.

Figure 4-9. Electronics - Circuit Board A9 - Dual +24 VDC Supply.

4.10 DESCRIPTION -- BLAST SHUTTER AND INTRACAVITY SHUTTER OPERATION (FIGURE 4-10)

An intracavity shutter is located within the laser resonator to make the system "eye" safe without required system shut off. Thermal stabilization is required for best modelocking, so that the lamp should remain on except during extended inoperative periods. The intracavity shutter should be opened during system operation to allow lasing. A red light indicates an open shutter or lasing condition, while the green indicates a closed shutter and nonlasing condition. Remote operation of this shutter is possible by shorting or switching a low impedance across the provided BNC connector. This closes the shutter.

A blast shutter covers the system output aperture to protect the system from spurious returns during firing of the SHIVA chains, that might damage components or detectors. Its operation is identical to the intracavity shutter described above.

Figure 4-10. Electronics - optical table - shutter systems box.

4.11 DESCRIPTION - CHOPPER REFERENCE SIGNAL CIRCUIT (FIGURE 4-11)

The chopper motor is a synchronous 3600 RPM AC motor. It drives a Z1 opening dual blade. The two blades are necessary to precisely adjust the required 50 percent duty cycle. A 1-2.29 drive pulley causes the blade to chop at:

$$\frac{3600}{60} \times 21 \times \frac{1}{2.29} = 550 \text{ Hz}$$

A reference for the PAR lockin amplifier is developed by optical pickup (LED-Phototransistor). The signal waveform is processed by a Schmidt trigger and a 50 ohm line driver to drive the long coaxial interconnection.

Figure 4-11. Electronics - optical table - chopper reference signal circuit.

4.12 DESCRIPTION - LASER HOOKUP AND OPERATION (FIGURE 4-12)

The Quantronix laser is mounted on the optics table, separated from its lamp supply, closed loop water flow, and heat exchanger. The following lists required connections.

1. A five wire cable brings in 208 3Ø at 40 amps/phase using 5 wires to the back of the lamp supply. There are three (3) phases, a neutral, and a chassis ground.
2. An AC interconnection cable goes from the lamp supply to the lower cabinet position to the pump, and electronics. Once this cable is in place, a "correct" phase rotation indicator light is operative and must be illuminated for proper pump rotation.
3. A large two wire HV encapsulated goes from the supply to the table for the lamp.
4. A smaller cable for the thermal and flow sensors also goes to the table.
5. Two water tubes, supply and return also go to the table.
6. A 120 VAC standard rip cord goes to the optics table.
7. Water lines from an external supply goes into the lower cabinet flowing through the heat exchanger.

From the modelocker driver

1. 120 VAC input
2. Sync output to sampling plugin
3. AO drive coax (maintain lengths) goes to an inline power meter, and on to the table.

From the electronics cabinet

1. 10 separate miniature coax cables mate with the connectors on the table.
2. 120 VAC input PAR
3. 120 VAC input electronics

The system is provided with various interlocks which must be closed for operation. An interlock on the laser cover opens when the cover is removed. A removable cap is attached to an interlock at the rear mirror, to prevent operation with rear output. Since the output is used for modelock pulse monitoring it is removed from the cap.

a. Electronics - Optical Table - Electronics Hookup

b. Electronics - Power Distribution Diagram

Figure 4-12. Laser hookup and operation.

The laser is turned on by

1. Turn on Key
 - a. Power Indicator will Light
 - b. Interlock Indicator Must Not Light
 - c. Level Indicator Must Not Light
2. Depress Pump
3. Turn on External Cooling Water to Heat Exchanger
4. Set Lamp Level to Half Scale, Depress Switch
5. When Lamp Lights, Set Level to 20.0 amps
6. Leave on Modelocker Driver at All Times.

4.13 DESCRIPTION - DETECTORS AND PREAMPLIFIER (FIGURE 4-13)

The detectors are biased and their output currents amplified by a transimpedance amplifier. The current node performs the differencing for the two currents required by the balanced detection process. The LH0032 is a high input impedance precision operational amplifier. The output drives a buffer amp and coaxial line driver. This buffer is required to drive the long coax cable return to the receiver.

In addition this buffer provide the isolation of the preamp from driving the large coaxial capacitance, required for stability.

Figure 4-13. Electronics - Optical Table - Detectors and Preamplifier.

4.14 ELECTRONICS CONTROL PANEL (FIGURE 4-14)

Junction	From				To			
	Board	Pin	Osm No.	Element No.	Board	Pin	Osm No.	Element No.
1	A8	17						
2		GRD						
3	A8	19						
4	A9	R						
5		GRD						
6	A8	4						
7		GRD						
8	A8	6						
9	A9	K						
10		GRD						
11				13 Switch				14
12				N/C				
13				16				11 Switch
14				11	A7, A8, A9	A-Z		
15	120 VAC	IN-GOLD			A7, A8, A9	A-Z		
16				17 Fuse				13
17	120 VAC	IN-HOT						16 Fuse
18				22				External Short
19				21 Switch	A1 U			
20				N/C				
21				23				19 Switch
22	A1	P						23 LED
23				22 LED				21
24				26 Switch	A1 W			
25				N/C				
26				28				24 Switch
27	A1	S						28 LED
28				27 LED				26
29				27				External Short
30				32 Switch				34
31				32 Switch				37
32		GRD						30, 31 Switch
33	A7	W						34 LED
34				30				33 LED

4.14 ELECTRONICS CONTROL PANEL (Continued)

Junction	From				To			
	Board	Pin	Osm No.	Element No.	Board	Pin	Osm No.	External No.
35	A5	K						36, 37 Pot
36		GRD						35, 37 Pot
37				35 Pot	A5 A			31
38	A5	M						Dither Ref Monitor
39	A3	U						40 Pot
40	A3	V						39 Pot
41	A4	K			A3 A			42
42			No. 7		A4 A			
43			No. 8					Chopper Reference
44	A2	K						45, 46 Pot
45	A3			44, 46 Pot				
46				44 Pot	A2 A			
47	A3	P						Boost Amp Monitor
48	A2	K						Lockin Input
49	A2	M						50 Pot
50				49 Pot	A2 D			
51	A2	X						53 Pot
52	A2	W						53 Pot
53				51, 52 Pot	A2 Y			
54	A3	K						Envelope Det Monitor

Figure 4-14. Electronics control panel.

5.0 SUPPORTING CALCULATIONS

5.1 CHARACTERIZATION OF THE SIGNALS

The time dependence of E field output of any CW laser may be written

$$E(t) = \sum_n E_n e^{i\omega_n t + i\phi_n} \quad (5-1)$$

where the summation is over several modes of frequency $\omega_n = \omega_0 + 2\pi n/T$ and positive, real amplitudes $E_n = E_0^0 \gamma_n$, where $\gamma_n \approx \exp(-an^2)$ describes the mode amplitude distribution. $E(t)$ is periodic in $T = 2L/C$, where L is the laser cavity optical length. When the laser is mode locked, the number of modes in oscillation generally increases, and all of the modes add in phase at some time which may be arbitrarily set equal to zero. All ϕ_n may then be set equal to zero.

The detector response when irradiated by the signal E_s and local oscillator E_{LO} is

$$R(\tau) = S |E_s + E_{LO}|^2 \quad (5-2)$$

where

$$\begin{aligned} S &= \text{detector responsivity} = \eta e/h\nu \text{ amp/watt} \\ \tau &= \text{time delay between } E_s \text{ and } E_{LO} \\ E_s &= E_s^0 \sum_n \gamma_n e^{i\omega_n(t+\tau)} \end{aligned} \quad (5-3)$$

$$E_{LO} = E_{LO}^0 \operatorname{Re} \left[\sum_n \gamma_n e^{i(\omega_n + \omega_{LO})t} \right] = E_{LO}^0 \sum_n \gamma_n e^{-i\omega_n t} \cos \omega_{LO} t$$

ω_{LO} = LO frequency offset.

Then the evaluation of (5-2) for the amplitude of the term at frequency

$\omega_{LO} \ll \omega_n$ is

$$\begin{aligned} I_s(\tau) &= 2S E_{LO}^0 E_S^0 \sum_n \gamma_n e^{i\omega_n(t+\tau)} \sum_m \gamma_m e^{-i\omega_m t} \\ &= 2S E_{LO}^0 E_S^0 \sum_n \gamma_n^2 e^{i\omega_n \tau} \end{aligned} \quad (5-4)$$

for $n = m$, since the IF bandpass excludes terms with $n \neq m$. From (5-4), the peak current occurs when $\tau = 0$, or

$$I_s(\text{peak}) = I_s(0) = 2S E_{LO}^0 E_S^0 \sum_n \gamma_n^2 \quad (5-5)$$

The dependence of $I_s(\text{peak})$ on laser power will now be calculated. The signal power is given by

$$\begin{aligned} P_S(t) &= E_S(t) E_S^*(t) \\ &= \left(E_S^0 \right)^2 \sum_n \sum_m \gamma_n \gamma_m e^{i(\omega_n - \omega_m)t} \end{aligned}$$

The average power is

$$\langle P_s(t) \rangle = \frac{1}{T} \int_0^T dt P_s(t) = (E_s^0)^2 \sum_n \gamma_n^2, \quad (5-6)$$

and the peak power is

$$P_s(\text{peak}) = P_s(0) = E_s^2 \left(\sum_n \gamma_n \right)^2 \quad (5-7)$$

Then from (5-5) and (5-6),

$$I_s(\text{peak}) = 2S \langle P_{LO} \rangle^{1/2} \langle P_s \rangle^{1/2}, \quad (5-8)$$

and it is concluded that the SNR calculations to follow depend on average powers rather than peak power.

5.2 THE CARRIER SIGNAL TO NOISE RATIO (SNR_c)

The rms shot noise at the output of a silicon diode is

$$(4 e I_{dc} B_{IF})^{1/2}, \quad (5-8A)$$

where

$I_{dc} = S \langle P_{LO} \rangle =$ direct current flow

$e =$ electron charge $= 1.6 \times 10^{-19}$ coul

$B_{IF} =$ IF bandpass, HZ.

Then the IF zero-to-peak to rms noise is

$$\text{SNR}_c(\tau) = \frac{I_s(\tau)}{(4e S \langle P_{LO} \rangle B_{IF})^{1/2}} \quad (5-9)$$

$$= \left(\frac{\eta \langle P_s \rangle}{h\nu B_{IF}} \right)^{1/2} \left(\frac{I_s(\tau)}{I_s(o)} \right),$$

where from (5-4),

$$\begin{aligned} \frac{I_s(\tau)}{I_s(o)} &= \frac{\sum_n \gamma_n^2 e^{i\omega_n \tau}}{\sum_n \gamma_n^2} \\ &= \frac{\sum e^{-2an^2 + i\omega_n \tau}}{\sum e^{-2an^2}} \end{aligned} \quad (5-10)$$

Typically, 20 to 50 modes are oscillating so that the summations in (5-10) can be approximated by integrals:

$$I_s(\tau) \sim \sum_{-\infty}^{\infty} e^{-2an^2 + i 2\pi n \frac{\tau}{T}} = \sum_{-\infty}^{\infty} e^{-2an^2} \cos \left(2\pi n \frac{\tau}{T} \right) \quad (5-11)$$

$$\approx \int_{-\infty}^{\infty} e^{-x^2} \cos \left[\frac{2\pi}{\sqrt{2a}} \left(\frac{\tau}{T} \right) x \right] \frac{dx}{\sqrt{2a}} \quad (5-12)$$

$$= \sqrt{\frac{\pi}{2a}} e^{-\frac{1}{2a} \left(\frac{\pi \tau}{T} \right)^2} \quad (5-13)$$

The validity for replacing (5-11) by (5-12) is seen to depend on the value of τ/T ; if $\tau/T > 1/12$, then argument of the cosine changes by greater than 30° for each increment of n by one and the continuous approximation is greatly in error. Therefore, (5-13) is good only near the peak at $\tau = 0$. However, if a is small (large number of modes oscillating) then (5-13) is narrow and (5-13) will be valid where $I(\tau)$ is large. For example, if N modes are oscillating, $a \approx 4N^{-2}$, and

$$\frac{I_s(\tau)}{I_s(0)} = e^{-\frac{1}{8} \left(\frac{N\pi\tau}{T} \right)^2} = e^{-1} \quad (5-14)$$

for

$$\left(\frac{\tau}{T} \right)_{e^{-1}} = \frac{2\sqrt{2}}{\pi N} \approx \frac{1}{N}, \quad (5-15)$$

so that this approximation for τ/T is adequate provided $N > 12$.

It is of interest to compare the width of $I_s(\tau)$ from (5-15) with the pulse width of $P_s(t)$:

$$\frac{P_s(t)}{P_s(0)} = \left| \frac{\sum_n \gamma_n e^{i\omega_n t}}{\sum_n \gamma_n} \right|^2$$

$$\left[e^{-\frac{1}{2} \left(\frac{\pi t}{T} \right)^2} \right]^2 \quad (\text{from 5-13 with } 2a \rightarrow a) \quad (5-15)$$

$$= e^{-\frac{2}{2} \left(\frac{\pi t}{T} \right)^2}$$

and

$$\left(\frac{t}{T} \right)_{e^{-1}} = \frac{1}{\pi} \sqrt{\frac{a}{2}} = \frac{\sqrt{2}}{\pi N} = \frac{1}{2} \left(\frac{\tau}{T} \right)_{e^{-1}} \quad (5-16)$$

The width of the response curve $I_s(\tau)/I_s(0)$ is therefore twice that of the mode locked pulse width.

5.3 THE DOUBLE LO TECHNIQUE FOR POSITION MEASUREMENT

As shown in the previous section, the IF current varies approximately as a gaussian with the delay time τ , which may be related to the difference in optical path lengths of the LO and signal arms (neglecting multiples of $1/2$ the cavity length):

$$X = \frac{cT}{2}. \quad (5-17)$$

In terms of X ,

$$f(x) \equiv \frac{I_s(\tau)}{I_s(0)} = e^{-(X/\sigma)^2} \quad (5-18)$$

where

$$\sigma = \frac{\sqrt{2}}{\pi} \frac{cT}{N} \quad (5-19)$$

When two LO paths are alternately presented to the detector by means of a chopper, the peak-to-peak modulated signal current (square wave) becomes

$$I_m(x) \sim Qf\left(X - \frac{\Delta}{2}\right) - f\left(X + \frac{\Delta}{2}\right) \quad (5-20)$$

where Δ is the optical path length separation of the two LO paths and Q is the amplitude mismatch of the two LO beams. The equalization of the path lengths consists of adjusting X for each of the amplifier arms so that $I_m = 0$ with a fixed LO configuration. (5-20) is plotted in Figure 5-1 for several values of $\Delta/2\sigma$ and for $Q = 1$.

MAY 1977

Figure 5-1. Variation of signal current with path length difference.

For small errors in X away from $X = 0$,

$$I_m(\delta X) \approx I_m(0) + \delta X I'_m(0)$$

$$= 0 + \delta X \left[\frac{2\Delta}{\sigma^2} e^{-\left(\frac{\Delta}{2\sigma}\right)^2} \right], \quad (5-21)$$

and the sensitivity to δX is described by

$$\text{SNR}_m(\delta X) = \left(\frac{\eta \langle P_s \rangle}{h\nu B_{\text{IF}}} \right)^{1/2} \left(\tau_i B_{\text{IF}} \right)^{1/2} I_m(\delta X), \quad (5-22)$$

$$= \left(\frac{\delta X}{\sigma} \right) F_1 \left(\frac{\Delta}{2\sigma} \right) \left[\frac{\eta \langle P_s \rangle \tau_i}{h\nu} \right]^{1/2} \quad (5-23)$$

where

τ_i = integration time of the phase lock amplifier.

$$F_1(X) \equiv 4X e^{-X^2}.$$

Equation (5-23) is appropriate for envelope detection of an IF carrier with $\text{SNR}_{\text{IF}} \gg 1$, and subsequent synchronous detection of the AM modulation with integration time τ_i .

The function $F_1(X)$ is plotted in Figure 5-2 and exhibits a maximum at $X = 1/\sqrt{2}$. The optimum optical pathlength difference Δ is therefore

$$\Delta = \sqrt{2} \sigma, \quad (5-24)$$

at which point

$$\text{SNR}_m(\delta X) = (1.7) \frac{\delta X}{\sigma} \left[\frac{\eta \langle P_s \rangle \tau_i}{h\nu} \right]^{1/2}. \quad (5-25)$$

Finally, an imbalance Q in the two LO powers does not effect the measurement provided the imbalance is not too large; the null point of $I_m(x)$ in (5-20) is $X = X_0 \neq 0$ and X_0 is the same for all amplifier channels because it is independent of the returned signal power.

MAY 1977

Figure 5-2. Dependence of SNR on the ratio $\Delta/2\sigma$.

5.4 LO BEAMSPLITTER ANALYSIS

Two specially fabricated beamsplitters provide the two LO optical pathlengths required for the system. In Figure 5-3, the two paths are

1. AB
2. ACDEFB

and they are alternately obscured by a chopper with blade spacings fabricated to match the spacing beams (1) and (2). The optical path difference between (1) and (2) is given by

$$\Delta = 4t(n^2 - \sin^2 \theta)^{1/2} = 6.44 \text{ cm} \quad (5-26)$$

MAY 1977

Figure 5-3. LO beamsplitter configuration.

and the beam spacing by

$$d = \frac{t \sin 2\theta}{(n^2 - \sin^2 \theta)^{1/2}} = 1.00 \text{ cm} \quad (5-27)$$

for $\theta = 45^\circ$, $n = 1.45$, and $t = 0.5$ in. From (5-16), (5-17), and (5-24), Δ is the optimum pathlength difference for the following pulsewidth:

$$(2t)_e^{-1} = \frac{1}{2} (2\tau)_e^{-1} = \frac{1}{2} \frac{2}{c} (2\sigma) = \frac{\sqrt{2}}{c} \Delta = 300 \text{ psec.} \quad (5-28)$$

It is of interest to examine the variation of SNR_m with the laser pulse width $2/c$, keeping Δ fixed. Equation (5-23) is rewritten

$$\text{SNR}_m(6X) = \left(\frac{6X}{\Delta} \right) F_2 \left(\frac{\Delta}{2\sigma} \right) \left(\frac{\eta < P_s > \tau_i}{h\nu} \right)^{1/2} \quad (5-29)$$

where

$$F_2(X) = 8X^2 e^{-X^2}$$

is plotted in Figure (5-1). If now Δ is fixed at 6.44 cm, the curve for F_2 shows that a pulse width (e^{-1} points)

$$\frac{2\sigma}{c} = \frac{\Delta}{c} = 215. \text{ psec}$$

is optimum, and that the loss in SNR_m is less than a factor of two if the pulse width falls between 134. and 430. psec.

It is finally noted that Figure 5-2 is simplified in that it does not consider polarization. When employed in the system, the polarization is p-wave on the first pass through the beamsplitters. The cat's eye and quarter

wave plate rotate the polarization by 90° so that S-wave polarization traverses the beamsplitters on the return pass. If the losses at the antireflection coated surfaces are neglected then the ratio of LO_1 to LO_2 power R is given by

$$R^{1/2} = \frac{r_s r_p}{t_s t_p} = \frac{(1 - t_s)(1 - t_p)}{t_s t_p}$$

where

$t_s(r_s)$ = s-wave transmission (reflectance)

$t_p(r_p)$ = p-wave transmission (reflectance).

If $t_s + t_p = 1$, then $R = 1$. This is the correct condition on the beamsplitter coating, replacing $R = t = 0.5$.

5.5 EFFECTS OF ABERRATIONS ON SNR

The aberrations in the return signal wavefront are unknown, but are expected to be on the order of one wave. A calculation of the signal loss incurred by 1) a wavefront tilt and 2) spherical aberration is given below for a gaussian intensity profile.

The heterodyned signal is proportional to an integral over the receiver aperture:

$$\text{Re} \int d\mathbf{r} E_s(\mathbf{r}) E_{LO}^*(\mathbf{r}), \quad (5-30)$$

where

$$\begin{aligned} E_s(\mathbf{r}) &= \text{return signal wavefront} \sim \sqrt{P_s} e^{i\phi - r^2/w^2} \\ E_{LO}(\mathbf{r}) &= \text{local oscillator wavefront} \sim \sqrt{P_{LO}} e^{-r^2/w^2} \\ \phi &= \text{signal wavefront aberration.} \end{aligned}$$

The receiver noise is proportional to $\sqrt{P_{LO}}$, so that the IF peak-to-rms noise ratio (SNR_{IF}) is proportional to

$$\text{SNR}_{IF} \sim \sqrt{P_s} \text{Re} \iint r dr d\theta e^{i\phi - 2r^2/w^2} \quad (5-31)$$

Wavefront Tilt

In this case, $\phi = \beta r \cos \theta$. If we define a full wave aberration such that $\phi = \pi$ for $r = w$, then $\beta = \pi/w$. The integral becomes

$$I = \text{Re} \int_0^\infty r dr \int_0^{2\pi} d\theta e^{i\beta r \cos \theta - 2r^2/w^2} \quad (5-32)$$

$$\sim \int_0^{\infty} r dr e^{-2r^2/w^2} J_0(\beta r)$$

$$\sim \exp \left[-\beta^2 w^2 / 8 \right] \quad (\text{Gradshteyn and Ryzhik} \\ \text{p. 717, No. 7})$$

where only the dependence on the wave tilt β has been retained, and the integral over r has been extended to infinity. For $\beta = \pi/w$, the reduction in SNR due to tilt is

$$\exp \left[-\pi^2 / 8 \right] = 0.29 \quad (5-33)$$

Spherical Aberration

In this case, $\phi = \alpha r^2$, and

$$I \sim \operatorname{Re} \int_0^{\infty} r dr \exp \left[i\alpha r^2 - 2r^2/w^2 \right]$$

$$\sim \operatorname{Re} \frac{1}{(i\alpha - 2/w^2)}$$

$$\sim \frac{1}{1 + (\alpha w^2 / 2)^2}$$

For $\phi = 2\pi$ when $r = w$, obtain $\alpha = 2\pi/w^2$, and the SNR reduction factor is

$$\frac{1}{1 + \pi^2} = 0.09 \quad (5-34)$$

Discussion

An alternate approach is to expand the signal field into a series of orthogonal modes. The number of modes required in the expansion is limited by the pin hole size in the spatial filter. A single mode LO beam selects out one of these signal modes, whose coefficient determines the heterodyned signal. A multimode LO might achieve a higher SNR, depending on the relative phases between modes. A complete analysis along these lines was not felt to be warranted.

The beam profile intensity may actually be "super" gaussian ($I \sim \exp \left[-r^\eta \right]$, $r > 2$), on which case the above results would become more complicated mathematically, but perhaps not qualitatively so, as $\eta \rightarrow \infty$, we return to the uniform beam profile, which exhibits nulls for several values of α and β . Whether these nulls occur for $\eta = 5$ has not been examined. In any event, the $\eta = 2$ case is convenient because one need not worry about finding himself in a null when a signal is present, or of aligning the receiver against a secondary maximum.

5.6 GHOST SIGNALS

Optical surfaces in the amplifier chain might produce reflections which could dominate the highly attenuated (10^{-9}) return from the surrogate target. Considering first specular reflections, the situation is illustrated in Figure 5-4. A beam with radius of curvature R_1 is incident on surface S with radius R_s . The transformation of a gaussian beam at an interface S may be described by the ABCD formalism*:

$$\frac{1}{q} \approx \frac{1}{R} - \frac{ik_0^2 \omega^2}{2n}$$

$$k_0 = 2\pi/\lambda_0 \quad (\lambda_0 = \text{wavelength in a vacuum})$$

$$n = \text{optical index}$$

$$R = \text{radius of curvature}$$

$$\omega = \text{spot radius (E-field } e^{-1} \text{ radius)}$$

$$q_2 = \frac{A q_1 + B}{C q_1 + D}$$

For the reflected beam in Figure 5-4,

$$\begin{vmatrix} A & B \\ C & D \end{vmatrix} = \begin{vmatrix} 1 & 0 \\ \frac{2n_1}{R_s} & 1 \end{vmatrix}$$

*A. Yario, "Quantum Electronics"

Figure 5-4. Geometry of a specular reflection.

and for the transmitted beam,

$$\begin{vmatrix} A & B \\ C & D \end{vmatrix} = \begin{vmatrix} 1 & 0 \\ \frac{-(n_2 - n_1)}{R_s} & 1 \end{vmatrix}$$

The reflected curvature is

$$\frac{-n_1}{R_2} = \text{Re} \left(\frac{1}{q_2} \right) = \text{Re} \left[\frac{\left(\frac{2n_1}{R_s} \right) q_1 + 1}{q_1 + 0} \right] = \frac{2n_1}{R_s} + \frac{n_1}{R_1},$$

or

$$-\frac{1}{R_2} = \frac{2}{R_s} + \frac{1}{R_1}, \quad (5-35)$$

and the refracted curvature is

$$\frac{n_2}{R_1} = \frac{-(n_2 - n_1)}{R_S} + \frac{n_1}{R_1} \quad (5-36)$$

The conventions used here are that the index is set negative for propagation along the -E axis, and R_S is positive if centered to the right.

Equation (5-36) may be used to trace through a series of surfaces, at each of which (5-35) is used to calculate the reflected power that is intercepted by the receiver. The heterodyne signal may be written as in (5-30) with the integral evaluated at the surface S:

$$E_{LO} \sim e^{-r^2 \left(\frac{1}{w^2} + \frac{i k_0 n_1}{2R_1} \right)} \quad (\text{LO field})$$

$$E_R \sim e^{-r^2 \left(\frac{1}{w^2} + \frac{i k_0 n_1}{2R_2} \right)} \quad (\text{reflected field})$$

$$I \sim \int dr E_{LO} E_R^* \quad (\text{peak IF current})$$

$$\sim \int_0^\infty r dr e^{-r^2 \left[\frac{2}{w^2} + \frac{i k_0 n_1}{2} \left(\frac{1}{R_1} - \frac{1}{R_2} \right) \right]}$$

The effective reflection coefficient is, for ρ = specular reflection = 0.1 percent for AR coatings,

$$\begin{aligned}
 R &= \rho \frac{I \left(\frac{1}{R_1} - \frac{1}{R_2} \right)}{I(o)} \\
 &= \frac{\rho}{1 + \left[\frac{k_o w^2 n_1}{4} \left(\frac{1}{R_1} - \frac{1}{R_2} \right) \right]^2} \\
 R &= \frac{\rho}{1 + \left(k_o w^2 n_1 \right)^2 \left(\frac{1}{R_s} + \frac{1}{R_1} \right)^2} \quad (5-37)
 \end{aligned}$$

using Equation (5-35). The propagation of the curvature across the spaces between the surfaces will be approximated by

$$R_1'' = R_1' + L, \quad (5-38)$$

where

L = spacing to next surface

R_1'' = radius of curvature at the new surface

This ray approximation should be adequate when the surfaces are far away from the focused beam waists.

Relations 5-36, -37, and -38 are now used to fill out the entries in Table 5-1), with $\rho = 0.001$. It is concluded that specular reflections are not a problem for the configurations analyzed.

If a surface is found to produce a substantial ghost, interference of the ghose with the target signal can be eliminated by adjusting their relative path lengths so that the peaks of the ghost response curve fall between those of the signal. Of course, the target signal is distinguishable from ghosts by its movement with path length adjustment.

TABLE 5-1. GHOST REFLECTANCES

Surface	Radius of Curvature R_s , mm	Incident Curvature $\frac{1}{R_1}$, mm ⁻¹	Beam Diameter 2ω , mm	Spacing Between Surfaces, L , mm	Optical Index, n	Effective Reflectance R
Spatial filter (2nd)						
1	270	0	44			7.8×10^{-12}
2	-2595	-1.86×10^{-3}	44	5	1.5	6.6×10^{-11}
3	2595	2.11×10^{-3}	44	961	1	1.8×10^{-11}
4	-270	1.91×10^{-3}	44	5	1.5	8.2×10^{-12}
Beam expander						
1	-129	0	21			3.5×10^{-11}
2	1240	3.85×10^{-3}	21	3	1.5	8.2×10^{-11}
3	2595	2.02×10^{-3}	44	248	1	1.9×10^{-11}
4	-270	3.82×10^{-3}	44	5	1.5	3.5×10^{-11}

Finally, diffuse reflectance of surfaces will be considered. The effective reflectance for a Lambertian reflector may be written

$$R' = \rho' \frac{\theta^2}{4} \quad (5-39)$$

where

ρ' = surface reflectance into 2π sterad.

$\theta = \frac{2\lambda}{w}$ = diffraction limited divergence of a gaussian beam of radius w .

$\pi 6^2/4$ is the solid angle intercepted by the receiver. It is seen that R' is largest for small w ; therefore, letting

$$2w = 21 \text{ mm}$$

$$\rho' = 5 \times 10^{-3},$$

obtain

$$R' = 4.6 \times 10^{-12}.$$

The behavior of (5-39) with ω tells us that no trouble will derive from diffuse reflectance; if the system works at all with a 1 or 4 mm beam at the beam-splitter, then it will work the presence of the larger w present in the amplifier chain.

5.7 SYSTEM PERFORMANCE ESTIMATE

The performance is contained in Equation (5-29):

$$\text{SNR}_m(\delta X) = \left(\frac{\delta X}{\Delta} \right) F_2 \left(\frac{\Delta}{2\sigma} \right) \left(\frac{\eta \langle P_s \rangle \tau_i}{h\nu} \right)^{1/2} \quad (5-29)$$

Substituting the values

$$2\sigma = \Delta = \text{LO spacing} = 6.44 \text{ cm}$$

$$F_2(1) = 2.9 \text{ (maximum)}$$

$$\eta = \text{photodiode quantum efficiency} \approx 0.2 \text{ at } \lambda = 1.06 \mu$$

$$h\nu = 2 \times 10^{-19} \text{ joules}$$

$$\tau_i = \text{phase lock amplifier integration time} = 1 \text{ sec}$$

$$\langle P_s \rangle = \text{signal power} \approx \langle P_L \rangle \text{ (average laser output power)}$$

$$\times 1/4 \text{ (attenuation from polarizer in signal path)}$$

$$\times 1/2 \text{ (attenuation from chopper in signal path)}$$

$$\times 10^{-9} \text{ (round trip attenuation in signal path for linearly polarized beam),}$$

5-29 becomes, for a carrier to noise ratio $\text{SNR}_c \gg 1$,

$$\text{SNR}_m = 503 \langle P_L \rangle^{1/2} \delta X. \quad (\delta X \text{ in mm}) \quad (5-30)$$

The above value of SNR_m is valid at all values of SNR_c if the carrier were synchronously demodulated. However, the present system employs envelope detection which degrades SNR_m if $\text{SNR}_c \leq 1$. This effect may be incorporated into Equation 5-30 by multiplying by the factor γ_1 which has been

calculated for a linear rectifier in Appendix A. The results of Appendix A are summarized in the curve given in Figure 5-4 (a linear rectifier is equivalent to an envelope detector with short integration time, and probably provides a worst case estimate for γ_1). SNR_c is obtained from 5-9:

$$\text{SNR}_c(\tau) = \left(\frac{\eta \langle P_s \rangle}{h\nu B_{IF}} \right)^{1/2} \left(\frac{I_s(\tau)}{I_s(0)} \right), \quad (5-9)$$

where

$$B_{IF} \approx 100 \text{ kHz}$$

$$\frac{I_s(\tau)}{I_s(0)} \approx e^{-1} \text{ (the point at which } \text{SNR}_m \text{ is maximized).}$$

Using these values and those incorporated in 5-30, we obtain

$$\text{SNR}_c = 13. \langle P_L \rangle^{1/2} \quad (5-31)$$

The laser output when stably mode locked is $P_L \approx 0.5$ watts, leading to

$$\text{SNR}_c = 9.$$

The observed SNR_c under these conditions is about 2.5, so that a degradation factor of $\gamma_2 \approx 0.3$ in SNR_c is experienced. It is seen from Figure 5-5 that $\gamma_1 \approx 1$ under these conditions, and 5-30 becomes

$$\text{SNR}_m = (503) \gamma_1 \gamma_2 \gamma_3 \langle P_L \rangle^{1/2} \delta X \approx 50 \delta X, \quad (5-32)$$

Figure 5-5. Degradation factor .

where $\gamma_1 \approx 1$, $\gamma_2 \approx 0.3$, and the additional degradation factor $\gamma_3 \approx 0.5$ is assumed to account for the losses in carrier duty cycle. If the reasonable assumption is made that $SNR_m = 5$ is adequate to assure a null, then 5-32 indicates a position accuracy

$$\left| \delta X \right| < \frac{SNR_m}{50} = 0.1 \text{ mm} \quad (5-33)$$

for an attenuation of 10^9 . The positional error over a range of attenuations is plotted in Figure 5-6, from which it is seen that the loss incurred with envelope detection is significant only for transmissions less than 10^{-9} .

Figure 5-6. Estimated position error versus signal path transmission.

5.8 APPENDIX CALCULATION OF DEGRADATION IN SNR_m DUE TO ENVELOPE DETECTION

Synchronous detection of a modulated carrier involves mixing with the unmodulated carrier. A linear rectifier or an envelope detector works equally well with AM modulation when the IF carrier signal-to-noise ratio (SNR_c) is greater than one. The rectifying diode recovers the correct phase of the carrier by attenuating the negative portion of the carrier cycle. When SNR_c falls below one, then this diode phase detection is often in error, and the final detection SNR_m suffers by a factor $\gamma_1 \leq 1$. γ_1 is calculated below for a linear rectifier (as compared to synchronous detection); this result is thought to be approximately correct for envelope detection as employed in the hardware.

Assume the initial (IF) waveforms:

$$\text{Signal} = P \cos p t$$

$$\text{Noise} = \eta_i = \eta_c(t) \cos p t + \eta_s(t) \sin p t,$$

where

$$\overline{\eta_i^2} = \psi_o$$

For synchronous detection (multiplication by $\cos p t$) the detector outputs are:

$$I_{dc} = P \cos^2 p t = P/2$$

$$\overline{\eta_o^2} = (\eta_i \cos p t)^2 = \frac{1}{4} \overline{\eta_c^2} = \frac{1}{4} \overline{\eta_i^2} = \psi_o / 4,$$

and

$$\text{SNR}_c = I_{dc} / \sqrt{\overline{\eta_o^2}} = P / \psi_o^{1/2} = (2x)^{1/2},$$

where

$$x \equiv P^2/2\psi_0.$$

For linear rectification with characteristic

$$I = \begin{cases} 0, & V < 0 \\ \alpha V, & V > 0 \end{cases},$$

The outputs are*

$$I_{dc} = \alpha \left(\frac{\psi_0}{2\pi} \right)^{1/2} e^{-x/2} \left[(1+x) I_0 \left(\frac{x}{2} \right) + x I_1 \left(\frac{x}{2} \right) \right] \quad (A-1)$$

$$\begin{aligned} \overline{\eta_o^2} &= \frac{2\alpha^2 \psi_0}{\pi^2} (x+1) - I_{dc}^2 \\ &= \alpha^2 \left(\frac{\psi_0}{2\pi} \right)^2 \left\{ \frac{4}{\pi} (x+1) - e^{-x} \left[(1+x) I_0 \left(\frac{x}{2} \right) + x I_1 \left(\frac{x}{2} \right) \right] \right\} \end{aligned} \quad (A-2)$$

where I_0 and I_1 are the modified Bessel functions. Limiting values of I_0 and I_1 lead to

*Rice, S. O., "Mathematical Analysis of Random Noise," Bell System Technical Journal, Vols 23, 24. Equations 4.2-3, -6.

$$\eta_o^2 (x = 0) = \frac{\alpha^2}{\pi^2} \psi_o (2 - \pi/2)$$

$$I_{dc} (x \gg 1) = \frac{\alpha^2}{\pi} = \frac{\alpha}{\pi} (2 \psi_o)^{1/2} x^{1/2}$$

$$\sqrt{\eta_o^2} (x \gg 1) = \frac{\alpha}{\pi} \psi_o^{1/2}$$

$$SNR_c = I_{dc} / \sqrt{\eta_o^2} = (2x)^{1/2} \text{ for } x \gg 1.$$

The detection problem at issue is that of an amplitude modulating square wave resulting in an input carrier amplitude that varies between P and P + ΔP. The SNR to an increment ΔP is

$$\frac{\Delta P}{\sqrt{\eta_o^2}} \frac{d I_{dc}}{dP}$$

and the ratio γ_1 is

$$\gamma_1 = \frac{\text{SNR for linear rectification}}{\text{SNR for synchronous detection}}$$

$$= \frac{\left(\frac{x}{2}\right)^{1/2} e^{-x/2} \left[I_o \left(\frac{x}{2}\right) + I_1 \left(\frac{x}{2}\right) \right]}{\left\{ \frac{4}{\pi} (x+1) - e^{-x} \left[(1+x) I_o \left(\frac{x}{2}\right) + x I_1 \left(\frac{x}{2}\right) \right] \right\}^{1/2}} \quad (A-3)$$

$$= \begin{cases} 1.0 & x \gg 1 \\ 0.96 (2x)^{1/2} & x \ll 1 \end{cases} \quad (A-4)$$

where the derivatives and asymptotic expressions for I_o and I_1 have been used. Figure 5-4 is a plot of Equation (A-3). The asymptotes in Equations (A-4) are useful in plotting the position error versus signal error transmission in Figure 5-6.

NOTICE

"This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research & Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately-owned rights."