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OPTICAL COMMUNICATION FOR SPACE MISSIONS

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Abstract

NASA/GSFC has played a leading role in the development of direct detection (DD) optical communications for space applications. The key challenges for optical communications have been in the development of reliable optical power sources and in the design of high performance pointing, acquisition and tracking systems mandated by the narrow widths of transmitted optical beams. These areas have been the focus for GSFC involvement in optical communications over the past few years. GaAlAs diodes and diode arrays are the most attractive technology for optical transmitters, and accordingly, GSFC has conducted extensive diode life testing and performance characterization studies on commercially available laser diodes. Pioneering work on dichroic and grating techniques for combining the power of several laser diodes has also been carried out. Other technology development activities at GSFC have included work on injection locked diode arrays for far-field pattern improvement, novel implementation of laser diode modulators, and development of advanced optical detectors for communications and tracking. GSFC work on optical systems development has been centered around brassboard hardware which has been developed to demonstrate optical link acquisition and submicrodian tracking/pointing performance. This system is referred to as the Pointing, Acquisition and Tracking System (PATS). A detailed computer simulation model of the PATS has been developed, and an extensive program has been initiated that will compare test and simulation data, and will provide an in depth understanding of the system design. Other systems work supported by GSFC has included the development of a 50 Mbps optical communications system demonstrating a bit error probability of 10^{-6} with a signal level of 55 photo-electrons per bit. Computer models have also been developed that describe the average and burst error statistics of the optical communications channel. The overall GSFC program supporting optical communications technology and systems is directed at a flight demonstration in the mid to late 90's. Space Station Freedom will serve as the space platform for this experimental flight system.

1. Overview

Optical communications systems offer the benefits of much smaller apertures and reduced weight and power in comparison with microwave systems, particularly at data rates in excess of 100 Mbps. Optical systems also avoid problems of RF spectrum allocation and interference. Accordingly, optical technology is a prime candidate for satisfying emerging very high data rate relay needs of NASA and the commercial satellite industry.[1,2] Direct detection (DD) optical systems also offer the benefits of simplicity relative to heterodyne systems. DD optical power need not be coherent and this enables the applications of power summing techniques which have demonstrated 200 mW beam powers and promise more than 1 W in the next few years. Furthermore, DD requirements for optical frequency stability are not as strict as those for heterodyne systems resulting in relatively wide tolerances on the choice of laser sources (e.g. combined diodes or multispectral mode) and on the temperature control of operating diodes. Finally, a DD receiver is significantly less complex than heterodyne, in that it does not track the optical frequency and need not be designed to diffraction limited tolerance.

The overall GSFC program in direct detection optical communications is aimed at developing the technology to meet the needs of NASA and the communications satellite industry. In Section 2, the GSFC view of the resulting requirements for optical systems at the component level and the system level is discussed. Providing assurance, via component technology development and system demonstration, that these requirements can be satisfied has been the major thrust of the GSFC program in optical communications. GSFC activities have included the development and testing of key components (discussed in Section 3) as well as the implementation of systems to demonstrate critical end-to-end performance requirements (discussed in Section 4). Increasingly, the primary goal of the program has become the development of proof of concept optical communications systems that will by form, fit, and function, demonstrate the readiness of the technology to support NASA requirements and those of the satellite communications industry. For the near term, such activities will be limited to ground based demonstrations due to resource limitations. However, the overall program is geared toward a flight demonstration of an experimental system as an Attached Payload on Space Station Freedom (SSF). This flight experiment is described in Section 5.

2. Requirements for Optical Communications Systems

2.1 Data Rates and Channel Quality

The primary requirements of NASA and commercial missions addressed by optical communications systems is the need for high data rate (100's of Mbps to Gbps) ISLs from LEO to GEO or across the qeosynchronous arc. The required channel quality varies from 10^{-6} to 10^{-9} BER depending upon the specific mission. Optical systems are attractive for this application because, as indicated in Figure 1, the required telescope apertures are quite small relative to the needed antenna apertures for RF systems. Reliable optical power is clearly one of the key requirements for optical communications, and GaAlAs laser diodes in the 0.8 to 0.9 um region are the prime candidates for this function. Performance requirements include high output powers in a single spectral and spatial mode, and stability under high data rate modulation with rise and fall times in the order of 400 ps. Furthermore, long lifetimes are required in order to support 5 to 10 year missions. With currently available single laser diodes and SI APD detectors, 30 cm to 50 cm apertures are required to relay 100 Mpbs to 1 Gbps across the LEO-GEO range. Power combined laser diode transmitters reduce the requirement to between 20 cm and 30 cm. Next generation improvements in laser diodes and detectors will permit even smaller apertures and a corresponding relaxation of pointing performance (Figure 2). Advances in single laser diodes, diode arrays, and power combining techniques, promise powers above 1W. In addition, reliable high peak power operation laser diodes will be able to reap the full advantages of quaternary pulse position modulation (PPM) over binary PPM. Finally, greater than 3 dB detector sensitivity improvement is likely from a new class of photodetectors currently under development.[3]

2.2 Spatial Acquisition

The small wavelength of optical communications systems result in extremely narrow beams which require precise pointing at the submicroradian level. Such accuracy is not obtained via open loop pointing so that establishing any optical communications link involves a spatial acquisition scenario in which the initial 1-10 mrad open loop pointing uncertainty typical of space platforms is reduced to <1 urad via mutual closed loop tracking. In an acquisition scenario, two cooperating terminals orchestrate a mutual scan/search. Typical scenarios contain multiple stages where initial broad beacons are successively narrowed to the diffraction limit as pointing accuracy is improved via closed-loop tracking. Achieving spatial acquisition reliably and within a short time (< 30 sec) is a strong driver for both low noise photosensitive area arrays, and for high power laser sources which can provide adequate signal strengths at GEO distances even broadened to 1 mrad and beyond.

2.3 Fine Tracking and Pointing

Typical space platforms contain high frequency vibrations which will create significant pointing jitter for attached instruments. For example, measurements on LANDSAT identified a pointing jitter of approximately 11 urad integrated out to 125 Hz. Clearly, if submicroradian pointing accuracy is to be achieved, such jitter must be suppressed by some 10 to 20 dB via pointing servomechanisms. Although there are many alternative approaches, the most commonly suggested one involves high bandwidth spatial tracking of the received beacon. With the transmitted and received signal sharing a common path the transmitted signal pointing is automatically compensated by maintaining the received signal spot at a reference position. The need to achieve 20 dB of jitter rejection out to a few hundred Hz is a driver for high performance pointing systems with servo bandwidths of 1000 Hz or more. In addition, high sensitivity tracking detectors with bandwidths of 5,000 to 10,000 Hz are needed.

2.4 Transmit Point-Ahead Correction

Because of the narrow beams and the fact that the platforms are in relative motion, a transmit pointing bias relative to the direction of the received signal is required. The required bias is equal to 2 V/c, where V is the relative velocity of the platforms perpendicular to their line of sight and c is the speed of light. For typical LEO to GEO applications, this tends to be on the order of $\pm$ 80 urad. Implementations for pointing-ahead ted to complicate the focal plane of the optical transceiver. One GSFC activity is exploring a simplified point-ahead scheme using a tracking area array detector.

3. Component Testing and Development

3.1 Laser Diodes Performance Characterization and Life Testing

Because the optical power source is perhaps the most critical component of an optical communications systems, GSFC began in 1984 a comprehensive testing program for single laser diodes.[4,5] The goal of this program has been to procure and evaluate commercially available high power GaAlAs laser diodes. For the Sharp (LT015MD) and Hitachi (HL8314E) laser evaluated at the GSFC, typical output powers are 30 mW average, 50-60 mW peak under 100 MHz square weave modulation, 50 percent duty cycle. These lasers are mostly single spectral mode, emitting between 810 and 840 nm, and single spatial mode, emitting in far-field patterns typically 10° by 25° at FWHM. Their polarization ratios are between 100:1 and 200:1. Wavefront errors are approximately lamda/30. Typical efficiencies are 0.7-0.9 W/A for sharp lasers and 0.4-0.6 for Hitachi. Results of these tests are summarized in Tables 1 and 2.

3.2 Laser Diode Power Combining

In order to achieve optical transmitter powers of several hundred milliwatts, GSFC has examined two combining techniques which incoherently sum the outputs of single element laser diodes. The first technique uses diffraction gratings to combine diodes in parallel while the second technique uses dichroic filters to combine diodes in series. Both techniques require stable wavelength separation of the individual laser diodes for efficient combining. Incoherent summing of single element laser diodes also builds in redundancy should one or two diodes fail catastrophically.

The Grating Laser Beam Combiner (GLBC) design uses the first-order diffraction from each grating to combine the laser outputs. This limits the overall efficiency to no better than the product of the first-order diffraction efficiencies of each grating. Current grating technology is capable of first-order diffraction efficiencies on the order of 85%. This limits the GLBC throughput efficiency to about 70%. These and other aspects of the GLBC are described in detail elsewhere.[6] A four laser diode GLBC has been built at GSFC and is nearing the test and evaluation stage. Figure 3 is a schematic of this GLBC.

An alternative to the GLBC is a combiner which employees dichroic filters to coalign the collimated outputs of multiple laser diodes. A proof of concept (POC) prototype using this approach has been developed by McDonnell Douglas Astronautics Company under contract to GSFC.[7] The Laser Power Summing System (LPSS) employs dichroic filters to spatially combine the output from seven laser diodes spaced at 2 nm intervals. Since this is a serial combining technique, the losses cascade such that the n^{th} laser diode reflects off n-1 dichroic filters. The losses multiply and soon a point of diminishing returns is reached such that the small increase in power afforded by the n+1 diode is offset by the added weight and optical alignment complexity. The practical upper limit appears to be between 10 and 15 laser diodes.

The optical system layout of the LPSS is depicted schematically in Figure 4. As shown, seven laser diodes are arranged along successive reflection lines of the dichroic filters. The performance of the final prototype system is summarized in Table 3. As indicated, the LPSS produced in excess of 170 mW of optical power from seven single element laser diodes with a composite beam divergence within 20% of the diffraction limit of a single channel.

4. System Development and Simulations

4.1 The GSFC Pointing, Acquisition and Tracking System (PATS)

The goal of the PATS program is to create a testbed to support design and specification of space-based optical direct detection communications terminals, and to demonstrate the

required spatial acquisition and tracking performance. The PATS is a brassboard/breadboard configuration of hardware capable of emulating space-based optical terminal pointing, acquisition, and tracking, and is supported by a detailed computer simulation of the hardware performance.[8]

4.1.1 Hardware Description

The PATS hardware currently consists of two terminals; a beacon simulator and a transceiver simulator, as depicted in Figure 5. The beacon simulator consists of a laser, two galvanometers which drive fine pointing mirrors, a noise generator, and a quad cell, and various optics. The beacon simulator initiates a test scenario by sending a laser beam to the transceiver. Two mirrors mounted on galvanometers induce spatial jitter in azimuth and elevation to simulate transceiver platform attitude motion. The transceiver locates and tracks the beacon simulator laser. During this process, the transceiver will send back a beam to the beacon simulator so that the transceiver nested control loop error can be measured.

The beacon quad cell senses the return beam and produces an error voltage proportional to the transceiver off-point angle. Either an oscilloscope or a monitor can be used to display this error signal. The transceiver simulator consists of the following components: a laser, two galvanometers, a vernier pointing system (VPS) controller, a gimbal assembly, a transconductance stage, a digital encoder, an all digital controller (ADC), a computer, a quad cell detector, a charge coupled device (CCD) camera, various optics, and several electronic modules. Figure 6 shows a view of the transceiver.

4.1.2 Preliminary Performance Analysis

The compensation for high frequency jitter is one of the key performance requirements for optical communications systems that PATS will demonstrate. For example, pointing jitter induced by space platform vibration can exceed 10 urad. Such jitter will be suppressed via high bandwidth tracking of an incoming beacon that will compensate for pointing jitter. Figure 7 is a plot of the disturbance rejection spectrum $|1-H(s)|^2$ for the current PATS configuration where H(s) is closed loop frequency response of the PATS pointing servomechanism. The 300 Hz resonance of the transceiver fine steering galvanometer is clearly visible. Figure 8 is a computer simulation output modeling PATS which shows how it would compensate for the pointing jitter power spectral density (PSD) measured on-board LANDSAT. The first frame of Figure 8 is the LANDSAT PSD which represents more than 11 urad rms jitter out to 125 Hz. The second frame shows the relevant portion of the PATS disturbance rejection spectrum. The third and final frame shows the PSD of the pointing error or untraced platform jitter. The total rms pointing jitter is roughly 0.5 urad and is dominated by the highest frequency components. It is interesting to note that the 0.5 u rad value is roughly the requirement for an optical system with a 20 cm aperture.

4.1.3 High Data Rate Transmitter/Receiver Systems

GSFC is supporting the development and testing of direct detection breadboarding systems using commercially available components. The prototype systems use a GaAlAs laser diode transmitter (lamda=834 nm) of 30mW maximum average power and a silicon avalanche photodiode (APD) GaAsFET feedback resistor type preamplifier. The signal format is a 4-slot pulse-position modulation (PPM), in which each pair of source data bits is encoded as an optical pulse in one of four slots within each transmitted word. A 50 Mbps system has been developed and has demonstrated a performance only 9 dB above the quantum limit by achieving a bit error rate (BER) of 10^{-6} at a received signal level of 55 detected photons per bit.[9]

Figure 9 illustrates the overall receiver design.[14] The optical signal is detected, amplified and split among sections which perform the maximum likelihood (ML) data estimation, slot synchronization, and word synchronization. For rectangularly shaped optical pulses, the ML estimator integrates the APD/preamp output signal over each time slot and then determines in which slot the largest value occurred for each word. For a source data rate R bits/sec and 4-PPM signal format, the slot duration $T_s = 1/(2R)$. The matched filter approximates an ideal integrator of duration T_s by splitting the input signal into four cable which have relative delays of 0, $T_s/4$, $T_s/2$, and $3T_s/4$, and then passing the sum of the delayed signals through a low pass filter. The matched filter output is then split among four cables having relative delays of 0, Ts, $2T_s$, and $3T_s$ whose outputs are compared at the proper instant to give an estimate of the received PPM word. The APD/preamp output is also sent through a pulse shaper which drives a phase lock loop (PLL) in order to recover the slot clock. The PPM word clock is recovered by locking a second PPL to the occurrence of back-to-back PPM pulses. No degradation in BER is evident with the recovered synchronization as compared to perfect (hard wired) synchronization when the received optical power is sufficient to produce 10^{-6} BER.

Theoretical models of the receiver were developed which accurately predict optimal system parameters and BER performance, A non-Gaussian model was necessary to simulate the APD output photocurrent. Use of the Gaussian model under conditions of negligible background radiation (less than one detected noise photon per slot) and very low APD dark current lead to an underestimate of the optimal APD gain, and therefore the BER would be higher than what is actually achievable when the proper gain is used. Figure 10 compares measured data with theoretical calculations of BER.

5.0 Proposed Flight Demonstration of Optical Communications

GSFC has proposed the development of laser communications transceiver (LCT) for Space Station Freedom which will be used to conduct a broad class of experiments in optical communications. The major areas of inquiry will include the achievable performance if a space-based LCT with regard to rapid beacon signal acquisition, fine tracking and pointing with submicroradian accuracy, and wideband communications at Gbps data rates with bit error rates as low as 10^{-9}. This will demonstrate the application of the LCT technology to future commercial and NASA communications needs including high data rate GEO-GEO and LEO-GEO communications links.

The approach toward the LCT design is to build a single optical bench and associated optics, including a 20 cm gimbaled telescope, which may be shared by alternative transmitter and receiver modules that embody competing technologies. Candidates for the transmitter modules include single GaAlAs diodes, multiple diodes power combined (for increased power) via dichroic beam splitters or gratings, and monolithic arrays of diodes. Candidates for tracking receiver modules include quadrant silicon avalanche photodiodes and high bandwidth charge coupled arrays.

A range of experiments will be conducted with the LCT in a variety of operational modes. The most important operational mode of the LCT is in concert with another cooperating laser transceiver where the overall performance of a mutual acquisition sequence, mutual tracking/pointing, and duplex communications can de demonstrated and measured. In fulfillment of these goals, GSFC is committed to upgrading its ground-based optical site to perform compatible LCT functions. Furthermore, GSFC is seeking additional opportunities for another laser transceiver in space at LEO (e.g., as a Shuttle attached payload) or at GEO (e.g., on NASA, ESA, or Japanese data relay satellite). A prime GEO opportunity is offered by the Advanced tracking and Data Relay Satellite (ATDRS) which will support a Pre-Operation Demonstration (POD) of a novel communications concept. Two of the three POD options under consideration involve laser communications: one would demonstrate a 650 Mbps LEO-ATDRS optical link, and the other a 2 Gbps ATDRS-ATDRS crosslink.

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TABLE 1: FAR-FIELD PATTERN DRIFT

FAR-FIELD PARAMETER		HITACHI HL8314E	SHARP LT015MD
$\frac{d(\text{mean})}{dt}$ (°/KHr)	0°	0.021 ± 0.015	0.007 ± 0.007
	90°	0.028 ± 0.031	0.009 ± 0.009
$\frac{d(\text{sd})}{dt}$ (°/KHr)	0°	0.051 ± 0.070	0.083 ± 0.084
	90°	0.017 ± 0.039	0.031 ± 0.024
AVERAGE FAR-FIELD CHANGES: PEAK-WANDERING AND CHANGES IN FWHM:			

TABLE 2: DIODE SPECTRAL STABILITY

DIODE	HOURS ($x10^3$)	MODAL DRIFT (nm/KHr)	MODE HOPS (NO. AND WAVELENGTH)
HITACHI			
7C0766	2.8	0.011 ± 0.028	(3) 834.7 -> 834.4 -> 834.7 -> 834.4
7C0765	4.5	0.031 ± 0.051	(many) 832.84 min -> 833.0 max
7C0764	4.5	0.0035 ± 0.028	(13) 833.2 min -> 835.0 max
7CO763	4.5	0.05 ± 0.043	(7) 833.2 min -> 833.7 max
7B1568	5.8	0.01 ± 0.034	(18) 840.8 min -> 841.7 max
		Avg. = 0.02113 Stand. Dev. = 0.034	
SHARP			
76-79310	4.5	0.0097 ± 0.033	(7-8) 834.8 min -> 835.0 max
70-79310	4.5	- 0.035 ± 0.036	(5) 832.8 min -> 834.2 max
69-79310	4.5	0.0082 ± 0.003	(2) 830.1 min -> 832.6 max
56-79310	6.2	0.0054 ± 0.027	(2) 834.3 min -> 834.9 max
52-79310	2.1	0.00071 ± 0.021	(2) 834.5 min -> 836.2 max
162-74530	4.0	- 0.0026 ± 0.020	(12) 828.6 min -> 830.6 max
		Avg. = 0.0118 Stand. Dev. = 0.0134	

TABLE 3
LASER POWER SUMMING SYSTEM PERFORMANCE CHARACTERISTICS

10-12937

ITEM	WORK STATEMENT	LPSS
NO. OF DIODES	7	7
WAVELENGTH	$0.8 < \lambda < 0.9$	.83 ± .006
DIODE POWER	$P_o < 20$mW*	$P_o > 30$mW
OPTICAL THRUPUT	>60	> 80%
MODULATION BANDWIDTH	250 MHz	52 kHz – 800 MHz
OUTPUT BEAM DIAM	0.8< d <1.2 cm	1.2 cm
CO-LOCATION OF BEAMS	±5% OF BEAM DIAM	± .05 cm
OUTPUT BEAM DIVERGENCE	NOMINALLY DIFFRACTION LIMITED	< 1.2 TIMES DIFFRACTION LIMIT
CO-ANGULARITY OF COMBINED BEAMS AT OUTPUT WINDOW	±5% OF BEAM DIVERGENCE	100 MICRORADIANS
EXTINCTION RATIO	—	> 20:1
MASS	5 kg	4.5 kg
VOLUME	.0135 m^3	.0082 m^3
OPERATING TEMP.	AMBIENT	AMBIENT
WARMUP TIME	t_w = 30 MIN	t_w = 5 MIN
UNATTENDED OPERATION	t_o > 60 MIN	t_o > 24 HRS

CURRENT TECHNOLOGY LINK ASSESSMENT

(40,000 km link; 10e-6; 6 db Margin; k=0.01; BPPM)

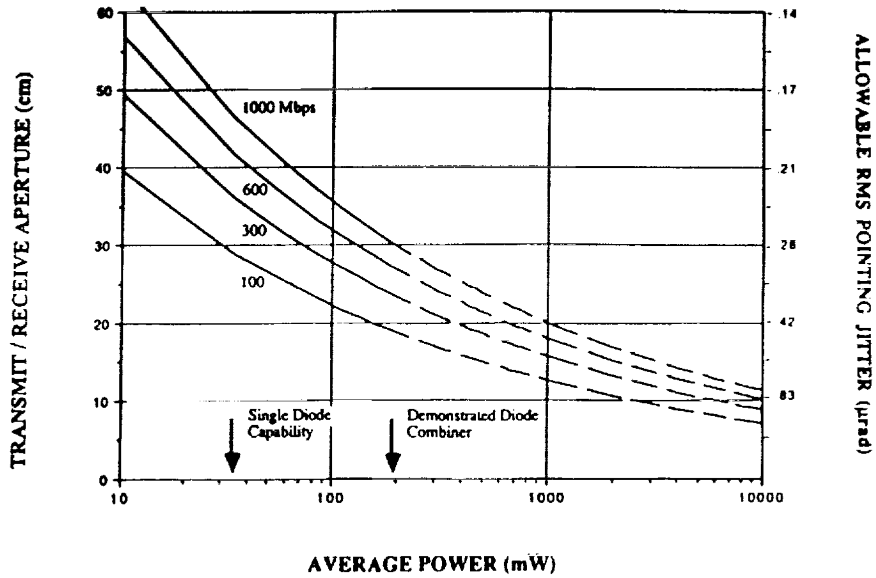

FIGURE 1

NEXT GENERATION LINK ASSESSMENT

(40,000 km link; 10e-6 BER; 6 db Margin; F=1; QPPM)

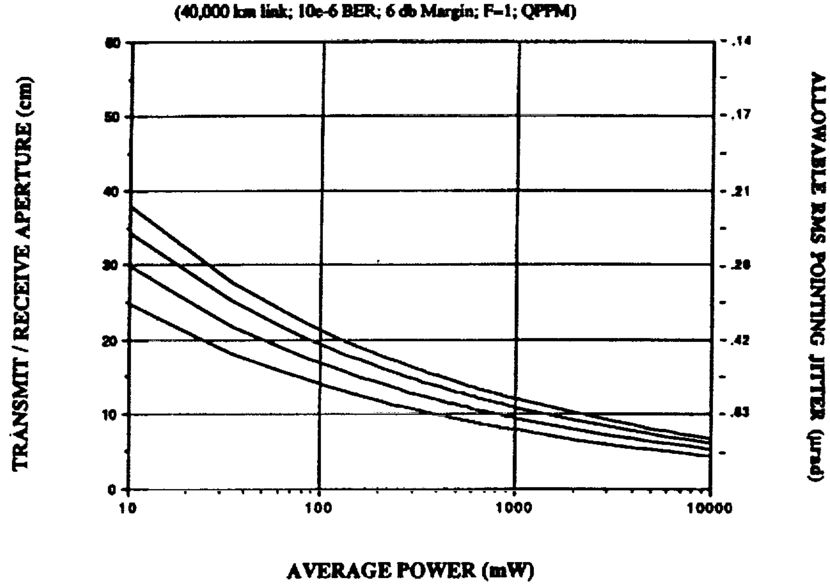

FIGURE 2

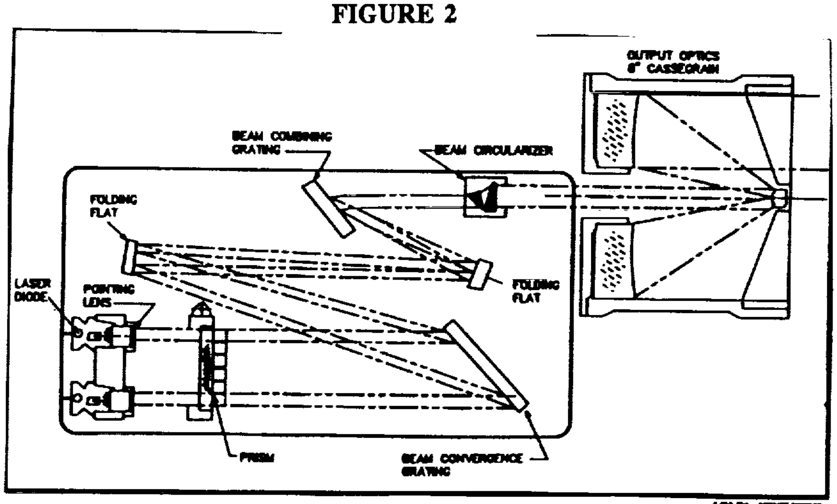

FIGURE 3: GLBC SCHEMATIC

LASER POWER SUMMING SYSTEM
LASER SOURCE ASSEMBLY

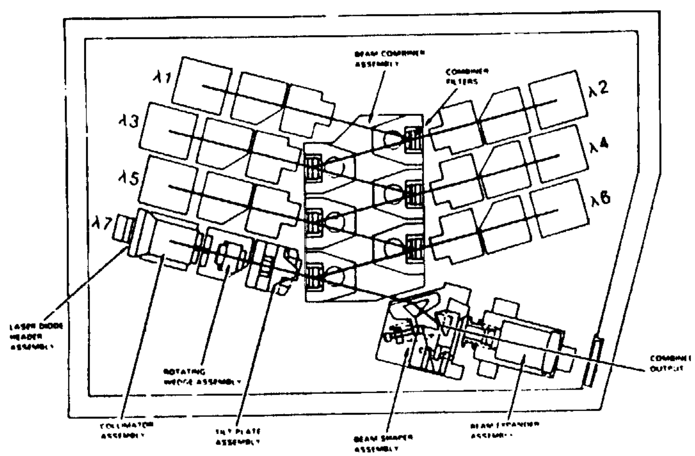

FIGURE 4

PATS Hardware Configuration

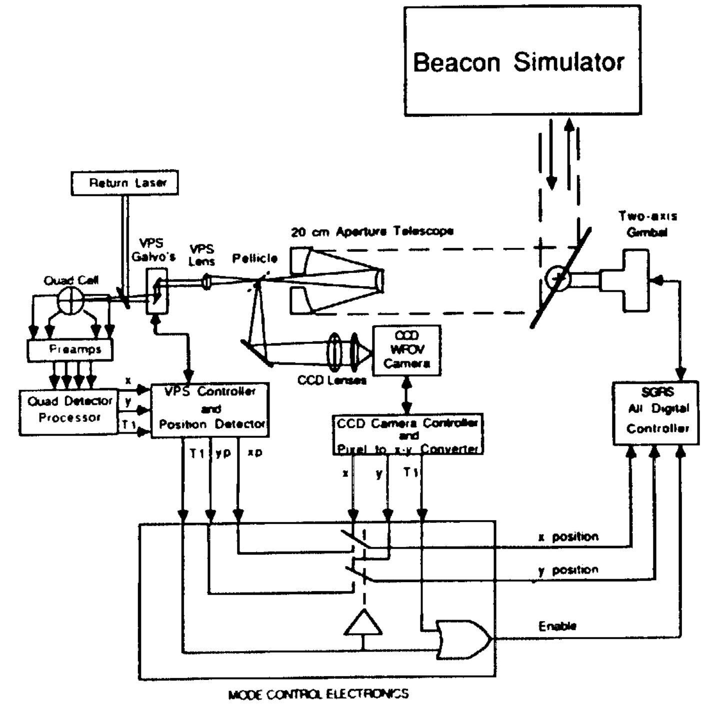

FIGURE 6

PATS Transceiver

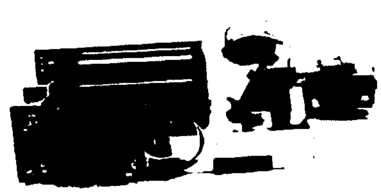

FIGURE 5

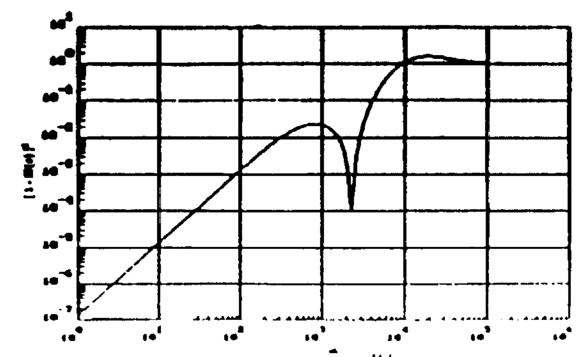

FIGURE 7

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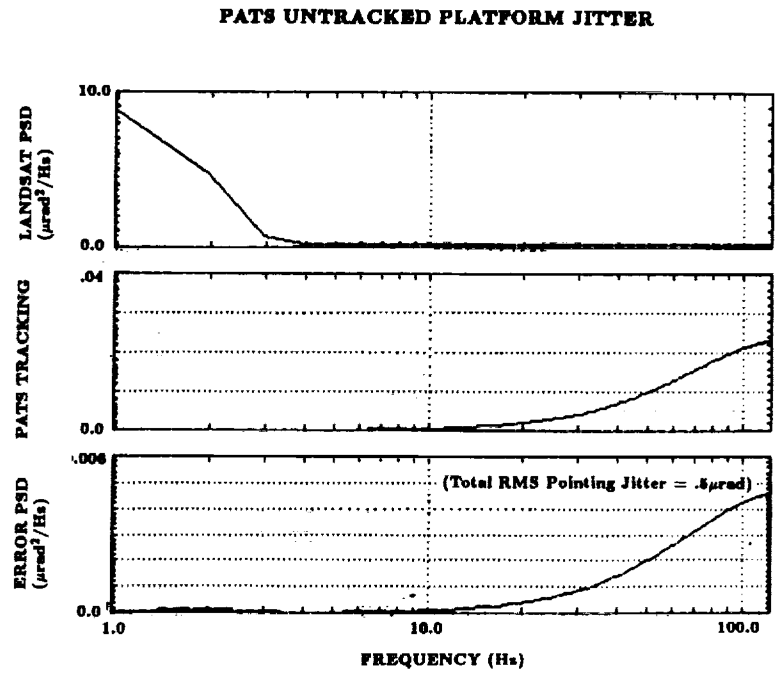

FIGURE 8

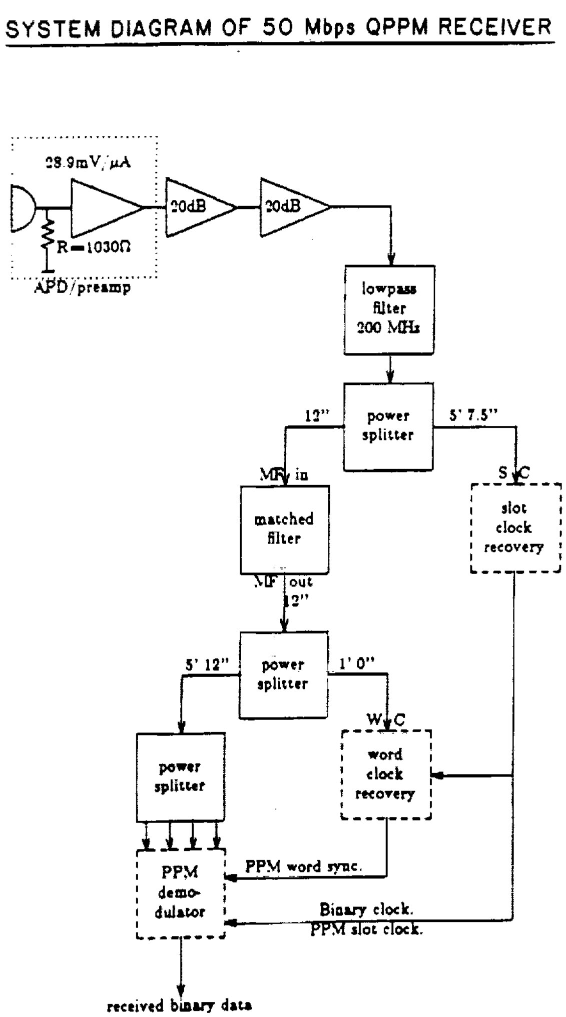

FIGURE 9

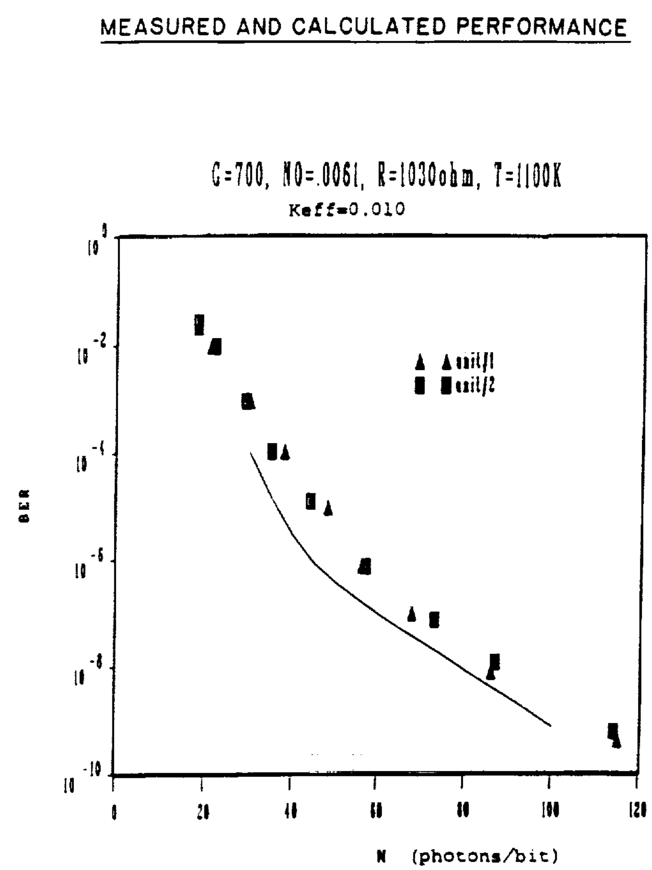

FIGURE 10

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