

# Plans for a STRV-2 to AMOS High Data Rate Bi-directional Optical Communications Link

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## ABSTRACT

BMDO (Ballistic Missile Defense Organization) has developed a high-data rate (155 Mbps – 1 Gbps) optical communications terminal that will be flown on the STRV-2 (space technology research vehicle) satellite. The satellite is scheduled for launch in November 1999, and NASA/JPL has been asked to investigate the use of the AMOS (Air Force Maui Optical Station) facility as a backup ground terminal to a small transportable terminal constructed by AstroTerra Corporation of San Diego. The ground terminal built by AstroTerra is designed to support a links out to 2000 km, and will be located at the Table Mountain Facility in Wrightwood, California. Subject to BMDO approval, the demonstration from AMOS will begin in early 2000. For the demonstration, the beam-director tracker telescope will serve as the uplink transmitter, and the 1.6-m telescope as the downlink receiver. The Maui ground stations will support bi-directional links out to the 3300-km maximum slant range of the satellite's pass.

**Key Words:** Optical communications, lasers, telescopes, STRV-2, AMOS, ground terminals, atmospheric scintillation, optical transmitters, optical receivers, Table Mountain

## 1. INTRODUCTION

Satellite communications has been long recognized as singular in its ability to provide full global connectivity, and communications between Earth orbiting satellites ranging from low Earth orbit (LEO), to geostationary (GEO) and ground stations are now routinely done. The delivery of large volumes of data such as is accumulated in hyperspectral and high-resolution imaging is driving the demand for bandwidth in a region of the electromagnetic spectrum that is already oversubscribed. Although strategies such as frequency reuse, and bandwidth efficient modulation (1), can provide more efficient use of allocated bandwidths these strategies may be hard pressed to meet the expected explosion in bandwidth requirements of the "internet in the sky". Using the several terahertz of bandwidth that are available at optical frequencies, to offload the demand on the tens of gigahertz available at radio frequencies (RF) is clearly a direct approach to solving the problem.

Optical communications offers a higher data rate communications in a small, low-mass, and low-power-consumption telecommunications subsystem than does RF. The higher operating optical frequencies result in small beam footprints at the ground station, and hence in a higher level of security in the communications channel. Recent successful optical communications demonstrations (2,3,4) have helped to answer some key technical questions on pointing and tracking from space and from the ground, and have raised the level of confidence in the technology. The STRV-2 (space technology research vehicle) lasercom demonstration (5) is one of the key optical communications experiments planned for the turn of the century (6,7), and is the first planned demonstration of a space-to-ground optical link at hundreds of megabits to gigabits data rates. AstroTerra Corp. of San Diego has built the lasercom space

terminal for this demonstration. They have also built a transportable ground terminal that will be located at TMF (Table Mountain Facility), Wrightwood CA(8). It is well known that the optical link is severely affected by cloud cover and the experience of past demonstrations (2, 4) supports the strategy of site diversity of ground stations, which the AMOS facility will provide.

The AMOS (Air Force Maui Optical Station) facility is currently being considered as a backup ground station to the TMF station. The system design for this facility calls for demonstrating the optical link at the farthest range allowed by the lasercom terminal. This will be done using narrow-divergence, high-powered diode lasers in a multi-beam configuration that has been previously shown to mitigate the effects of atmospheric turbulence on the uplink (4). In this paper we present the plans for the AMOS ground telescopes to support a proposed high-data-rate bi-directional optical communications demonstration between AMOS facility and the STRV-2's lasercom terminal. In section 2.1 we present the overview demonstration, and give the link analysis for the optical beam propagation to, and reception from the satellite. In section 2.2 we describe the uplink strategy for the beacon and communications beams. The designs for the transmitter and receiver optical trains are given in sections 2.3, and the transmitter and receiver electronics are described in section 2.4. The summary is presented in section 3.

## 2. EXPERIMENT

### 2.1 Experiment Overview

The demonstration from the AMOS facility is expected to begin during the first quarter of calendar year 2000 and extend for six-months. Figure 2.1.1 shows the concept of the bi-directional lasercom demonstration between the AMOS facility and the STRV-2 satellite. The satellite will be placed in a 69°-inclined elliptical orbit with a 410-km perigee, and a 1750-km apogee. The uplink transmitter is the 0.8-m BDT (beam director/tracker) telescope, and the receiver is the 1.6-m telescope located in the same building complex. The operations scenario calls for the satellite to "know" its location, and with the lasercom terminal's telecommunication lasers on, to begin its acquisition scan pattern searching for the 852 nm uplink beacon when the ground station is expected to come within the terminal's acquisition field-of-view. After the terminal acquires the beacon, it transitions to the tracking mode and transmits its 100  $\mu$ rad wide ( $1/e^2$ ) telecommunications beam (9) to the ground station.

Both the uplink and downlink telecommunications wavelengths are 810 nm, and the data is OOK modulated on to the laser beam. The downlink telemetry will be in one of the lasercom terminal's three operational downlink modes, namely:

- (i) Transmission of a preset PRBS (pseudo-random bit stream) downlink pattern retrieved from the on board memory and sent repetitively for the duration of the pass.
- (ii) Regeneration and polarization multiplexing of an uplink data stream. In this mode the effective downlink data rate is 2 X the uplink rate
- (iii) Downlink of 20 Mbytes of stored data received from the MWIR (medium wave infrared) instrument on board

The first two operational scenarios will enable measurement of the link characteristics under different atmospheric conditions. The transmission format for the telecommunications link will be PN 7 coded PRBS, and downlink bit and burst error rates will be measured at data rates of 155 Mbps, 325 Mbps, 500 Mbps and 1 Gbps. The third mode will be a 194 Mbps downlink, and a 20 Mbytes data file will be repetitively transmitted to the ground for the duration of the pass.

Current plans call for supporting demonstration opportunities that meet the following criteria:

- (i) The satellite must be at greater than  $30^\circ$  elevation. This restriction is due to the BDT dome (9).
- (ii) The satellite will be sunlit to facilitate acquisition by the ground station.
- (iii) The demonstration period for any pass must be longer than five minutes.

The basic operations scenario is as follows:

1. A high-accuracy satellite ephemeris file is delivered to AMOS where it is converted into separate telescope-pointing files for the transmitter and receiver telescopes.
2. The sunlit satellite is first acquired in the field-of-view of the receiver telescope when it is at about  $10^\circ$  elevation. The transmitter telescope is set to track the satellite even while its field-of-view is obscured by the dome.
3. The receiver telescope tracks the satellite, and when the satellite is boresighted time-tagged encoder position readings are processed by the Kalman filter. This reduces the uncertainty in the satellite's predicted position.
4. The transmitter telescope visually acquires the satellite when it raises above  $30^\circ$  elevation.
5. The transmitter telescope tracks the satellite. When the satellite is boresighted, time-tagged readings of the encoder positions are processed by the Kalman filter.
6. The transmitter telescope pointing direction is offset by the point-ahead angle. This can be as much as  $20 \mu\text{rad}$  to  $50 \mu\text{rad}$  over the expected link ranges

Initially, the uplink telescope will also track the satellite using a telescope-pointing file generated from the satellite ephemeris file. However, once the satellite raises above  $30^\circ$  elevation and can be visually tracked by the BDT telescope, the pointing file will be similarly modified using the Kalman filter approach. The telescope-pointing file will then be further modified by adding the slowly-varying point-ahead-angle correction. Once acquired and tracked twenty beams will be uplinked to the satellite. Four of these are wide divergence beacon beams that add incoherently in the far field, and sixteen are the narrower divergence telecommunications beams.

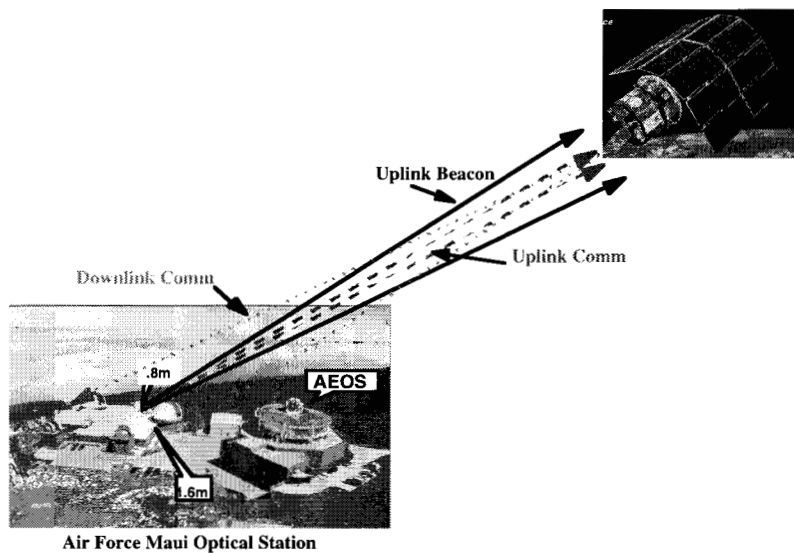


Figure 2.1.1: Bi-directional lasercom demonstration between the STRV-2 satellite and AMOS using the 0.8-m BDT telescope for beacon and telecommunications uplink and the 1.6-m telescope for downlink reception.

## 2.2 Analysis

The downlink analysis from the lasercom terminal to the 1.6-m receiver in Table 2.2.1 shows that at the 3000-km range, the link margin is substantial, 14 dB. The downlink beam width and transmitted

optical power for the four left-hand/ right-hand circular polarized (LHCP/RHCP) lasers were based on the measured performance of the lasercom terminal (10). The transmission of the receiver optical train was based on the published telescope transmission (9) and on the estimated losses of the components shown in Figure 2.3.2.1.

Table 2.2.1: Analysis for downlink transmission from STRV-2 lasercom terminal to the 1.6-m AMOS receiving telescope

STRV-2 To AMOS				
Link Summary				
Link Range	3.00E+03 km			
Data rate	5.00E+05 kbps	On-Off		
		Keying		
Coded BER	1.00E-06	No		
		Coding		
Transmit power	0.14 W average	280.00 mW (peak)	24.47 dB	
				m
Transmit losses	100.0 % transmission		0.00 dB	
Transmitter gain	101.5 urad beamwidth		93.25 dB	
Pointing losses			-0.97 dB	
Space loss			-273.36 dB	
Atmospheric losses	52.1 % transmission		-2.83 dB	
Receiver gain	1.60 m aperture diameter		135.71 dB	
Receiver optics losses	16.9 % transmission		-7.73 dB	
Received signal	5.83E+03 photons/pulse	0.72 uW (peak)	-31.45 dB	
				m
Background signal level	1.10E+01 photons/slot	1.35 nW		
Required signal level	2.20E+02 photons/pulse	26.94 nW (peak)	-45.70 dB	
				m
Link Margin			14.24 dB	

Figure 2.2.1 shows the measured BERs as a function of irradiance on the primary telescope for RHCP and LHCP incident on the lasercom terminal receiver. Our preliminary estimate of the uplink optical train transmission is 33%. With these losses, we calculate that at the 3300 km range 16 lasers emitting 1.17 W of optical power will provide the approximately 1 nW/sq.cm irradiance required to support BERs of 1E-6 and 1E-3 at data rates of 325 Mbps and 500 Mbps, respectively.

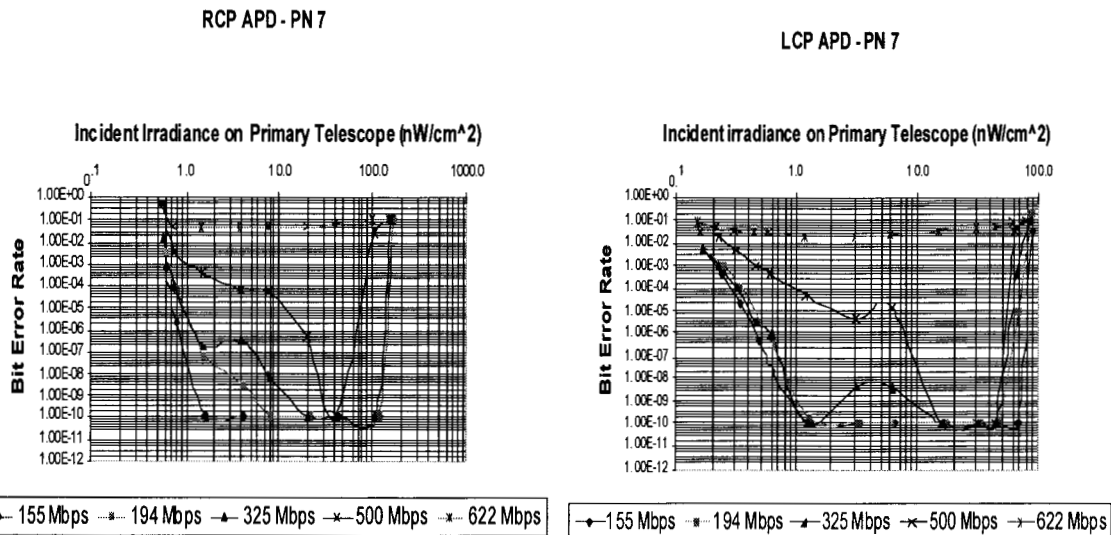


Figure 2.2.1: BER vs. incident irradiance for LHCP and RHCP at the input aperture to the lasercom terminal.

The required beacon uplink power was based on the measured camera response characteristic shown in Figure 2.2.2. In these calculations, we have baselined the smaller 3.8-cm diameter camera as the primary tracker and assumed a gain setting of "0" in the CCD electronics circuitry. The four beacon

lasers transmitted through the BDT telescope will provide approximately 240 pW/sq. cm at 3300 km range. This is approximately a 5-dB margin above the 80 pW/ sq. cm baseline.

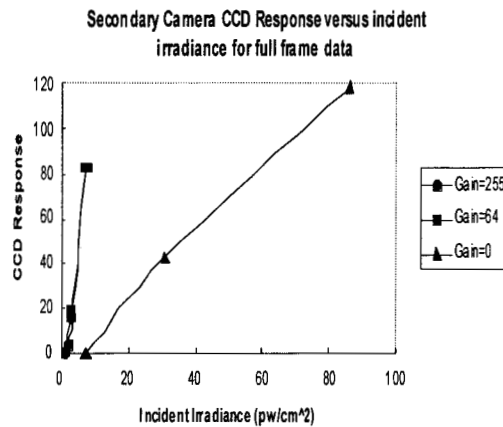


Figure 2.2.2: Shows the secondary camera (3.8 cm-diameter) response as a function of incident irradiance for three gain settings.

## 2.3 Optical Design

The design of the transmitter and receiver optical trains are described in the following two subsections. The BDT and 1.6-m telescope prescriptions provided by AMOS. These data along with the data on the performance of commercial-off-the-shelf optical components ( e.g. laser diodes, lenses etc.) were used in the Code-V optical design program to generate the transmitter and receiver optical performances given in this paper.

### 2.3.1 Transmitter Optical Train

A schematic of the transmitter optical train preliminary design is shown in Figure 2.3.1.1. The approach uses a multi-beam uplink strategy with sixteen 810 nm communications lasers non-coherently combined in the far field to mitigate the effects of atmospheric scintillation. The lasers are mounted in a circular plate arranged in four groups of four at coude so that, at the BDT's primary mirror, the lasers within each subgroup are separated by approximately 11-cm and by about 22 cm between subgroups. The divergence of the lasers from the BDT telescope is nominally 65  $\mu$ rad.

Each laser transmitter consists of a Spectra Diode Labs (San Jose, CA) model SDL5421 laser that is mated to an anamorphic microlens, to circularize the beam, by Blue Sky Research (San Jose, CA). The peak output power from these lasers is 150 mW, and they can be operated over a range of modulation formats from cw with 150 mW average power output, to 1 GHz and 50% duty cycle with 75 mW average power.

Four 852-nm lasers are interspersed with the communications lasers at 90° intervals on the laser mounting plate at coude shown in Figure 2.3.1.2. These lasers have a divergence of 94  $\mu$ rad and serve as a beacon for the lasercom terminal to acquire and track the ground station. They are wavelength-stabilized and will support acquisition and tracking using either the lasercom terminal's 13.7-cm diameter primary camera with its 0.01 nm wide atomic line filter or the 3.8 -cm diameter secondary camera with the 4 nm wide interference filter. Here, the effects of atmospheric scintillation are mitigated by a combination of a multi-beam uplink and spatial separation (50-cm) of the beams

separation on the 80-cm BDT primary mirror by greater than the coherence cell size,  $r_c$ , of the atmosphere.

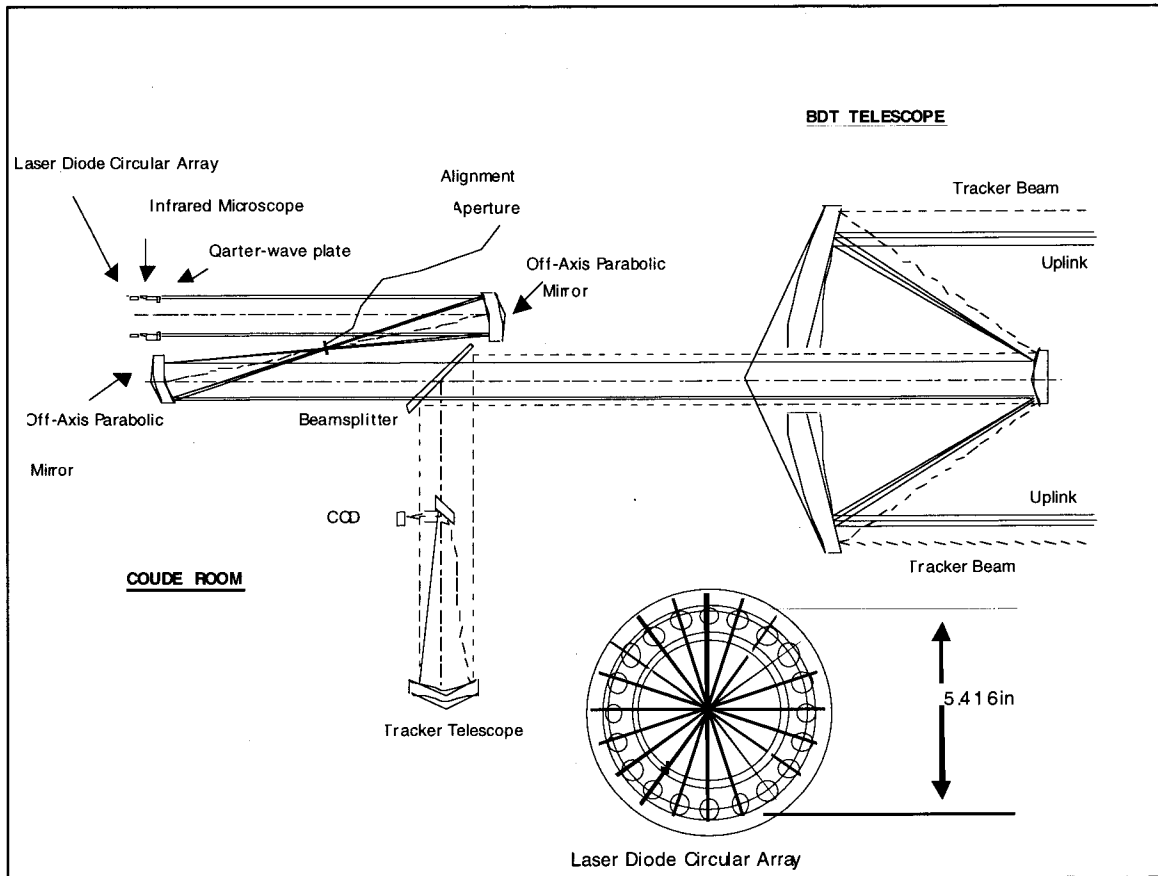


Figure 2.3.1.1: Schematic of the ground transmitter optical train shows the multi-beam design. Twenty laser beams are coupled through the coude path of the BDT telescope. The sixteen 810 nm communications laser beams diverge from the telescope at  $65 \mu\text{rad}$ . The four 852-nm beacon lasers have a divergence of  $94 \mu\text{rad}$ .

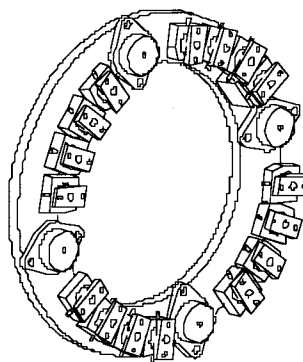


Figure 2.3.1.2: Schematic showing four beacon and sixteen communications lasers on mounting plate.

To point the uplink beam, the sunlit spacecraft is visually acquired and tracked using a tracking telescope and the 1 milliradian field-of view CCD camera in the BDT coude path as shown in Figure

2.3.1.1. The large field-of-view at the transmitter allows the satellite to remain visible within the field even after the ephemeris file is adjusted for the large 50  $\mu$ rad point-ahead angle.

## 2.3.2 Receiver Optical Train

Figure 2.3.2.1 is a schematic of the downlink receiver optical train. The receiver electronics are described in detail in Section 2.4. The RHCP and LHCP 810 nm lasercom downlink signals received at the 1.6-m telescope are first collimated and are then reflected from a dichroic filter that reflects the near-IR and transmits wavelengths shorter than 750 nm. The reflected light is then made incident on a 10-nm wide interference filter to reject any IR background radiation from the sky. A zeroth order quarter-wave plate is then used to convert the two orthogonal circular polarizations into two orthogonal linear polarization states. A high extinction ratio polarizing beamsplitter then spatially separates the two linearly polarized beams that are then focused onto two high speed large area (~150 micron diameter) silicon APD (avalanche photodiode) detectors. A field stop further suppresses the light from the sky background by limiting the APD's field-of-view to 60  $\mu$ rad, enough to accommodate flexure of the optical bench and to a lesser extent atmospheric seeing effects.

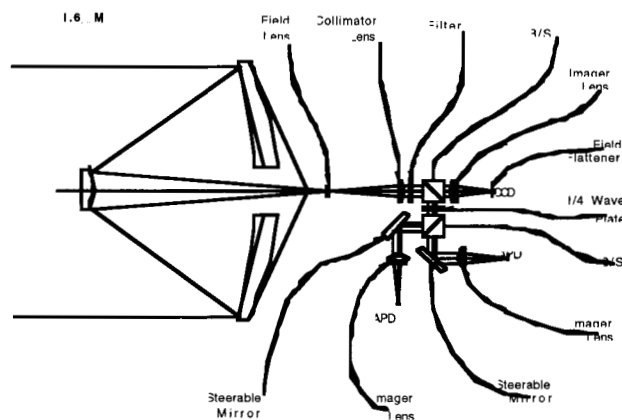


Figure 2.3.2.1: Schematic of the ground receiver optical train shows the beam paths for the two polarization states (RHCP and LHCP) downlinked from the satellite. The optical train components are assembled and aligned on a breadboard and hard mounted to the rear blanchard of the 1.6-m telescope. The diagram also shows the CCD beam path for tracking the sunlit satellite.

The tracking camera at the receiver operates in the video format and has a 1.5 arc-minute field-of-view. The design calls for camera sensitivity to detect stars down to 13<sup>th</sup> visual magnitude.

## 2.4 Transmitter and Receiver Electronics Design

A schematic of the data generation and receive systems for the ground terminal is shown in Figure 2.4.1. The transmitter system will be integrated with the 0.8 m BDT telescope and the receiver system the 1.6 m tracking telescope. A Tektronix GigaBERT1400 variable rate PRBS (pseudo-random bit stream) generator capable of generating data at up to 1.4 Gbps will be used at the transmitter facility to demonstrate the regeneration of an uplinked data stream. The transmitter will generate a PN 7

formatted PRBS data stream at data rates of 155, 325 and 500 Mbps. It will be programmed to provide the required ECL (emitter coupled logic) voltages up to a maximum 2 V amplitude.

The GigaBERT output will be coupled into a 16 channel cross-point switch to replicate the data stream across the 16 lasers. The switch is a 1 x 16 fanned out and de-skewed chip, Vitesse model 6250 with tunable phase delays to ensure that the 16 communication lasers are OOK modulated in-phase. Each diode will be powered by a voltage supply with bias and current-level adjustment circuitry. The ECL output signal from the switch will be coupled to a Hytek high-speed current driver, HY6110, that will modulate the 200 mA of current to the laser. The output of the HY6110 is then fed through a 50-ohm coax transmission line to the laser diode.

To evaluate the link performance, we will measure the bit error rate (BER) using the data streams described in section 2.1. The downlinked RHCP and the LHCP optical beams detected by the high bandwidth (450 MHz) Si APD detectors are amplified in the detector module that, in addition to the APD consists of a transimpedance amplifier. The output of this module goes to a high bandwidth-limiting amplifier to ensure optimal signal strength at the Uniphase model BCP510 clock and data recovery (CDR) unit. With an input signal of 5 mV to 500 mV, this CDR unit can recover data in several different formats automatically at rates from 50 Mbps to 2.5 Gbps. The recovered data output by the CDR unit is transmitted to the model GigaBERT1400Rx receiver that measures the BER at 1 Hz. The BER measurements are time tagged and stored on the computer (PC) for future analysis of the BER vs. received power as measured by the APD's DC output channel. These data can provide statistics on the bit and burst error rates of the link. Analysis of the eye diagrams of the data stream will also be done using a 1 Gsample/s sampling oscilloscope. This will be most useful if the jitter on the data stream precludes the CDR from locking onto the signal.

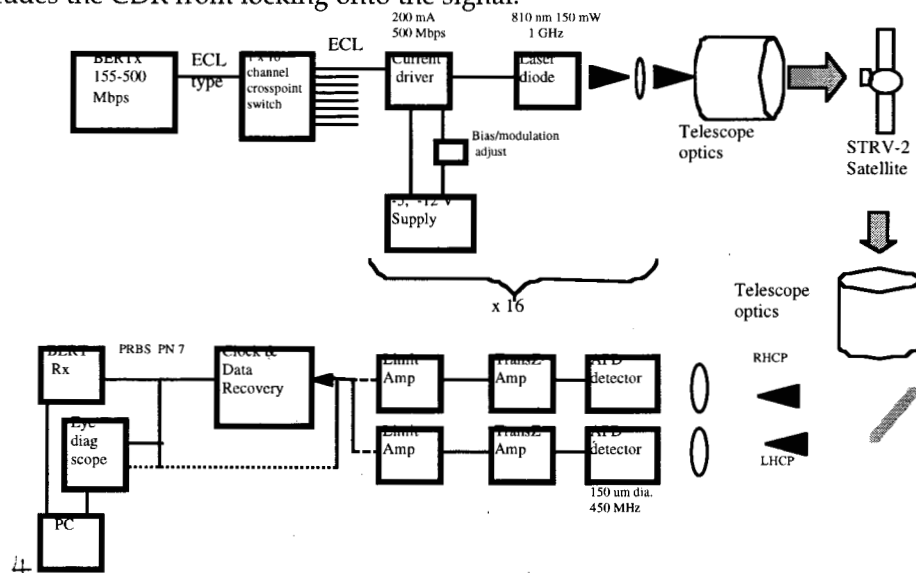


Figure 2.1: Block diagram shows the laser driver and communications electronics for the satellite uplink and the receiver electronics for recovering the two polarization states of the satellite downlink.

### 3. SUMMARY

We have described the plans for using the AMOS BDT and 1,6-m telescopes to support the lasercom demonstration with the STRV-2 satellite. The ground stations have been designed to transmit up to 500 Mbps to the satellite and to detect up to a 1 Gbps downlink data stream. The optical and electronic designs of the transmitter and receiver systems have been described in detail along with an overview of the planned operational scenario. The satellite is scheduled for launch in the last quarter of 1999, with operations beginning during the first quarter of year 2000.



## 4. ACKNOWLEDGMENTS

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