ATR
IWOSC '90

International Workshop
on
Optical Space Communication

Yoji Furuhama

Proceedings

December 6 and 7, 1990
ATR, Kyoto, Japan

ATR Optical and Radio Communications Research Laboratories

International Workshop on Optical Space Communication
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Contents

Opening Session

Session 1 Research on Optical Space Communications I
Chairman: Dr. Yasuo Hirata (KDD)

Session 2 Coherent Technologies for Optical Space Communications
Chairman: Dr. Masayuki Fujise (ATR Optical and Radio Comms. Res. Labs.)

Session 3 Research on Optical Space Communications II
Chairman: Dr. Tadashi Takano (The Institute of Space and Astronautical Science)

3-3 "Recent developments in laser technologies for optical space communications"
David L. Begley (Ball Aerospace Systems Group)

3-4 "Recent developments in high power optical source technology for space communications"
Richard Craig (Spectra Diode Laboratories)

Session 4 Research on Optical Space Communications III
Chairman: Dr. Koji Yasukawa (KDD)

4-1 "Free-space simulator for laser transmission"
Masayuki Fujise (ATR Optical and Radio Comms. Res. Labs.)

4-2 "Effect of microaccelerations on an optical space communication system"
Manfred E. Wittig (ESA ESTEC)

4-3 "Research on OSC and optical space technologies at ISAS"
Tadashi Takano (The Institute of Space and Astronautical Science)

Opening Session

Opening Address

Yoji Furuhama

ATR Optical and Radio
Comms. Res. Labs.

IWOSC '90
December 6 and 7, 1990, ATR, Kyoto

Opening Address

Yoji Furuhama
ATR Optical and Radio Communications Research Laboratories

It is a great pleasure for me to welcome all of you to the "International Workshop on Optical Space Communication: IWOSC '90". I would like to thank each and every one of you for your interest, and your efforts in helping us make this workshop possible, especially those who have traveled great distances and taken valuable time from very busy schedules. We are particularly fortunate in having with us five scientists and engineers from the U.S.A. and three from Europe.

This workshop has been organized by ATR Optical and Radio Communications Research Laboratories to provide an opportunity to exchange information and views on advanced research for optical space communication technology, as well as information on existing and future optical space communication projects worldwide. This workshop has been supported by the Ministry of Posts and Telecommunications, the Science and Technology Agency, the National Space Development Agency of Japan, and the Institute of Electronics, Information and Communications Engineers in cooperation with ATR International.

ATR, or more precisely, Advanced Telecommunications Research Institute International, was established in the spring of 1986, with support from industrial, academic, and governmental organizations, to serve as a major center for basic and advanced telecommunications R&D. "ATR" is the generic name for five organizations, namely ATR International and four R&D corporations supported by ATR International. ATR Optical and Radio Communications Research Laboratories is one of the ATR R&D corporations.

One of the basic principles behind ATR's establishment is the desire to contribute to international society. Our goals are the promotion of basic technological research, and the exchange of researchers and information between research institutions in Japan and abroad. In short, ATR commits itself completely to doing its part to help usher in the coming international society.

The ultimate goal of ATR Optical and Radio Communications Research Laboratories is to establish technologies that will allow anyone, at any time and in any location to communicate with anyone else. From this premise we are conducting basic research in optical and radio communications, focusing on space and mobile communications and communication devices based on artificially modulated material structures. Optical space communication is one of our research targets. We have begun research on basic technology for the realization of future optical space communication.

Optical space communication technology has been studied for two decades. This technology is expected to be operational in the early 21st century. An actual optical space communication experiment using a satellite has not yet been conducted. Within the next several years, Japan, ESA and NASA will conduct optical space communication experiments using satellites. However, it will not be easy for any of these organizations to have more than two satellites constantly available for these experiments. I hope that this workshop leads to the first step in international cooperation in optical space communication in addition to giving us a chance to exchange information and views on optical space communication research and the space program.

In this workshop, a breadboard model of the Laser Communication Equipment unit is exhibited in meeting room #05 on this floor through the collaboration of Communications Research Laboratory, the Ministry of Posts and Telecommunications, Toshiba Corporation, NEC Corporation, and the National Space Development Agency of Japan. The Laser Communication Equipment is to be installed on the ETS-VI satellite scheduled to be launched in 1993. All workshop participants are invited to view this exhibition which is opened to the public here for the first time.

I hope that we can discuss our mutual interests, and that this workshop will be a milestone in the development of optical space communications technology.

Session 1

Research on Optical Space Communications I

1-1

Overview of the NASA/GSFC optical space communication program

Michael E. Fitzmaurice

NASA Goddard Space
Flight Center

IWOSC '90

December 6 and 7, 1990, ATR, Kyoto

OVERVIEW OF THE NASA/GSFC OPTICAL SPACE COMMUNICATION PROGRAM

MICHAEL W. FITZMAURICE

ABSTRACT

NASA has maintained for many years a broad technology program aimed at the development of satellite optical communication systems for use in the near earth environment. The NASA program is focused at the Goddard Space Flight Center (GSFC) and emphasizes direct detection methodologies. The key challenges have been in the development of reliable optical power sources, sensitive wideband receivers, 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 in recent years.

At this time, communication systems are being developed on three levels: (1)a laboratory 50 MBPS test bed, (2)a 650 MBPS "flight-like" demonstration system, and (3)a 1200 MBPS experimental flight system for Space Station Freedom (SSF). The laboratory testbed has been built and is currently in the integration and test phase. The "flight-like" demonstration system is in the final part of the design phase with fabrication starting within 6 months. The SSF experimental system is in a definition study phase, with detailed design expected to start in 1992. In orbit testing is dependent on SSF schedules, but is currently planned for 1997. Each of these systems have some common features; all use 6-10 inch telescope apertures and require sub-arc second pointing stability. In addition, 4 slot pulse position modulation using AlGaAs lasers and silicon avalanche photodiodes is utilized.

The systems describe above are point-to-point, single access communication systems. However, a very different type of system which permits multipoint-to-point communication at rates up to 3 MBPS is also being developed. This system is being designed to the multi-access requirements of NASA's next generation data relay satellites, and offers the potential for large weight and volume savings as compared to S band implementation.

BIOGRAPHY

Dr. Fitzmaurice received his B.S. degree in Mechnical Engineering in 1964, and the M.S degree and Ph.d in Electrical Engineering in 1966 and 1970 respectively. Each degree was awarded by the University of Maryland at College Park.

Currently, Dr. Michael W. Fitzmaurice is the Assistant Division Chief for Satellite Communication Systems in the Instrument Division at the GSFC. In this role, he is responsible for the development of both microwave and optical communication technology for future NASA missions. He has recently been selected as the Principal Investigator for the Space Station Laser Communication Transceiver.

Prior to this position, Dr. Fitzmaurice served as the Branch Head of GSFC's Electro-optic Instruments Branch. This organization was responsible for a wide range of internationally recognized accomplishments in the application of lasers to satellite tracking, altimetry, atmospheric sensing, and space communication. This work established the technological foundation for the laser systems now under development for EOS, MARS Orbiter, and Space Station.

"OVERVIEW OF THE NASA/GSFC OPTICAL SPACE COMMUNICATION PROGRAM"

① Distance measurement
space to earth

② altimetry
mantle:

③ Communication in free space,
(Space Station Freedom

Laser ranging

INTERNATIONAL WORKSHOP ON OPTICAL SPACE COMMUNICATION
DEC. 6-7, 1990
KYOTO, JAPAN

MICHAEL W. FITZMAURICE
NASA/GSFC

PRESENTATION OUTLINE

1. NASA MOTIVATION FOR OPTICAL COMMUNICATION

2. CURRENT SYSTEM DEVELOPMENT ACTIVITIES/SINGLE ACCESS

3. OPTICAL MULTI-ACCESS SYSTEM CONCEPT

OPTICAL COMMUNICATIONS
— NASA PERSPECTIVE —

ADVANTAGES

- SMALLER ANTENNAS
  - —S/C REAL ESTATE
  - —REDUCE INERTIA, REACTION TORQUES
- NO FREQ. ALLOCATION PROBLEMS
- NO INTERSYSTEM INTERFERENCE
- UNLIMITED CHANNEL CAPACITY

APPLICATIONS

- VERY HIGH DATA RATE X-LINKS, LEO-GEO LINKS
- MEDIUM DATA RATE PROX. OPS. LINKS (SSF) Space Station Freedom
- LOW DATA RATE MULTI-ACCESS LINKS (ATDRS) 2~3 Mbps.

25k.

GSFC OPTICAL COMMUNICATION PROGRAM
- CONTRACTOR SUPPORT -

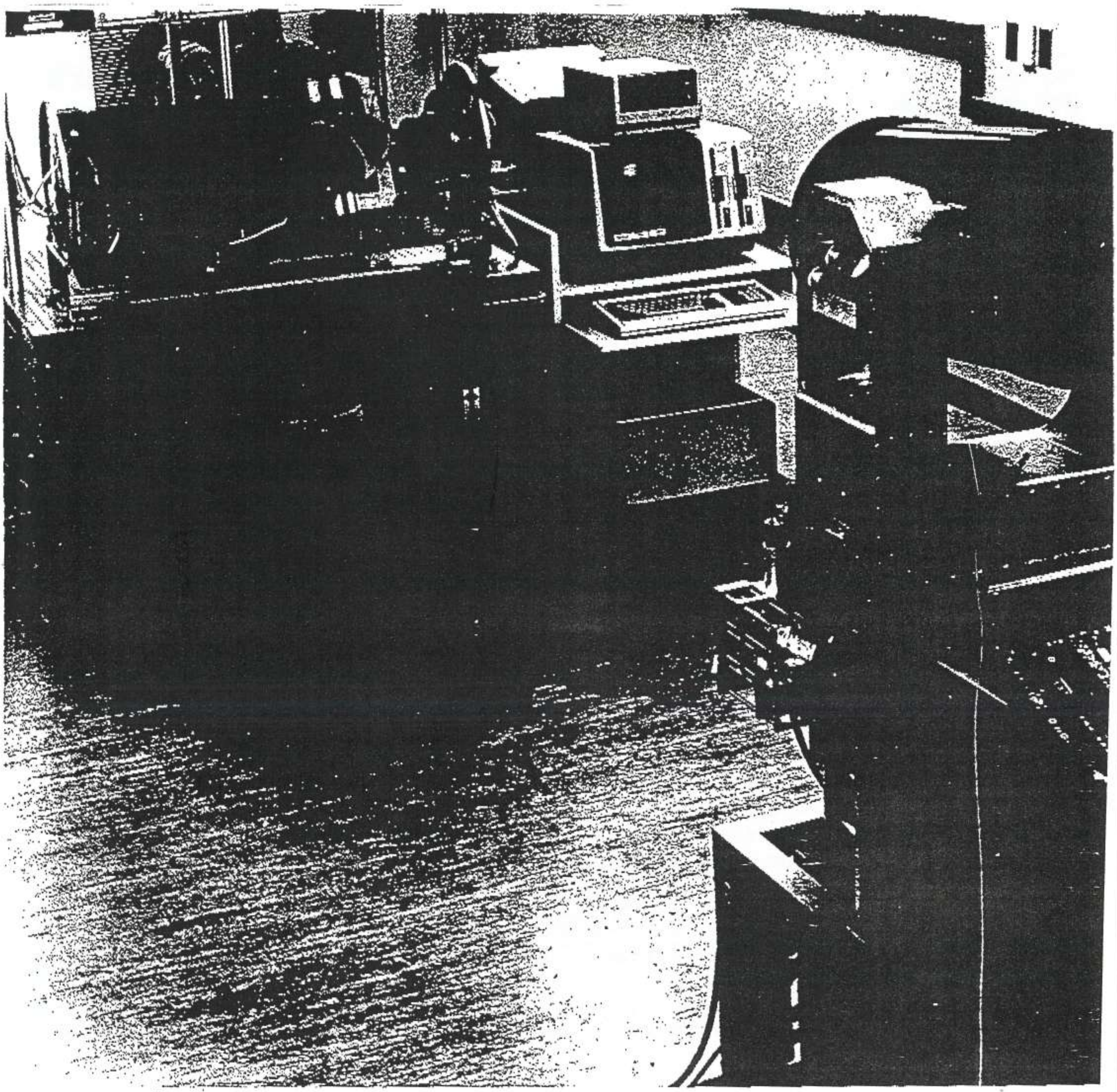
- ATR
- BALL AEROSPACE
- BELL LABS
- EASTMAN KODAK
- EER
- GALAXY MICROSYSTEMS
- GE/RCA
- HUGHES
- ITE
- JOHNS HOPKINS UNIV.
- LASER DATA TECHNOLOGY
- LIGHTWAVE ELECTRONICS
- MCDONNELL DOUGLAS
- MARYLAND UNIV.
- NAVTROL
- PERKIN ELMER
- PLESSCOR
- SPECTRA DIODE LABS
- SSAI
- STANFORD TELECOM
- SWALES
- TRW

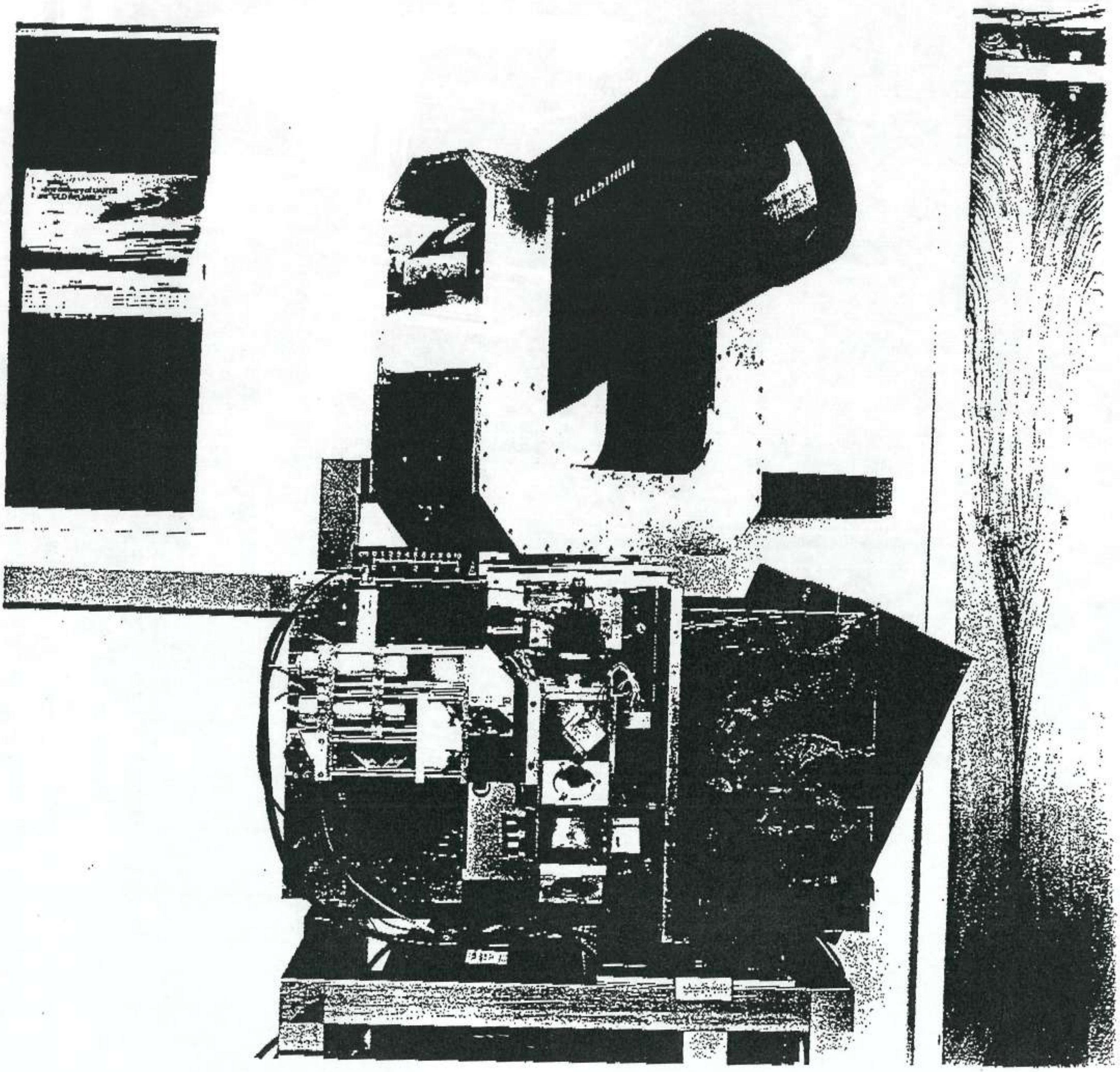
SYSTEM DEVELOPMENT ACTIVITIES

1. LAB TEST BED/INTEGRATION PHASE
   - 2 AUTONOMOUS TERMINALS
   - LEO/GEO CONFIGURATION, 50 MBPS
2. "FLIGHT-LIKE" DEMONSTRATION TERMINAL/DETAILED DESIGN PHASE
   - SINGLE TERMINAL, 20 CM OPTICS, HEMISPHERICAL POINTING
   - 650 MBPS, DUPLEX
3. SPACE STATION LASER COMMUNICATION TRANSCEIVER (LCT)/ DEFINITION STUDY
   - 1200 MBPS SPACE-TO-GRD.
   - 300 MBPS GRD.-TO-SPACE

OPTICAL COMMUNICATIONS TEST BED

- 2 INDEPENDENT, FULLY AUTONOMOUS TERMINALS
- CONFIGURED AS LEO AND GEO TERMINALS
- CONDUCT TESTS, OBTAIN DATA ON "SYSTEM-LEVEL" ISSUES
    - ALTERNATE ACQ. SCENARIOS
    - ACQ., COARSE TRACK, FINE TRACK, HANDOVER DYNAMICS
    - COARSE/FINE TRACK CONTROL SYSTEM COUPLING
    - PLATFORM JITTER REJECTION VERSUS MODELS
    - TECHNIQUES, PROCEDURES FOR IN-FLIGHT ALIGNMENT
    - XMIT/REC ISOLATION, SCATTERED LIGHT CONTROL
    - BIT ERROR STATISTICS
- COMPARE MEASUREMENTS VERSUS ANALYTICAL MODELS, IMPROVE MODELS





LEO TERMINAL CHARACTERISTICS

GIMBAL ASSEMBLY

- 280 CM, F/10 TELESCOPE
- INDUCTOSYN ENCODERS, INTERPOLATION TO 20 BIT RESOLUTION

ACQUISITION

- GIMBAL SCAN UNDER SW CONTROL
    - RASTER
    - SPIRAL
    - FIXED POSITION
- CCD ARRAY, VARIABLE FRAME RATE, 0.56° FOV
- "GREATEST OF" DETECTION, LOCAL BACKGROUND SUBSTRACTION

TRACKING

- QAPD, ± .175 MR CAPTURE FIELD
- 2 AXIS PZT BEAM STEERER
    - ±6 MR CONTROL
    - 1-2 KHZ BANDWIDTH

COMMUNICATION

- 50 MBPS, DUPLEX
- QPPM
- 48 PHOTONS/BIT @ 10^{-6} BEP

ご説明
ご協力し

NASA
Goddard Space Flight Center
Greenbelt Maryland 20771

[redacted]

GEO TERMINAL CHARACTERISTICS

GIMBAL

- 2 AXIS, 32.5 BY 18.3 CM BE FLAT
- 20 CM EFFECTIVE APERTURE
- BRUSHLESS DC TORQUE MOTORS
- 14 BIT OPTICAL ENCODERS, INTERPOLATION TO 27 BITS RESOLUTION
- LIGHT WT., HIGH RIGIDITY (BERYLLIUM, TITANIUM, ALUMINUM)

ACQUISITION

- CCD ARRAY
- ± 0.4° FOV

TRACKING

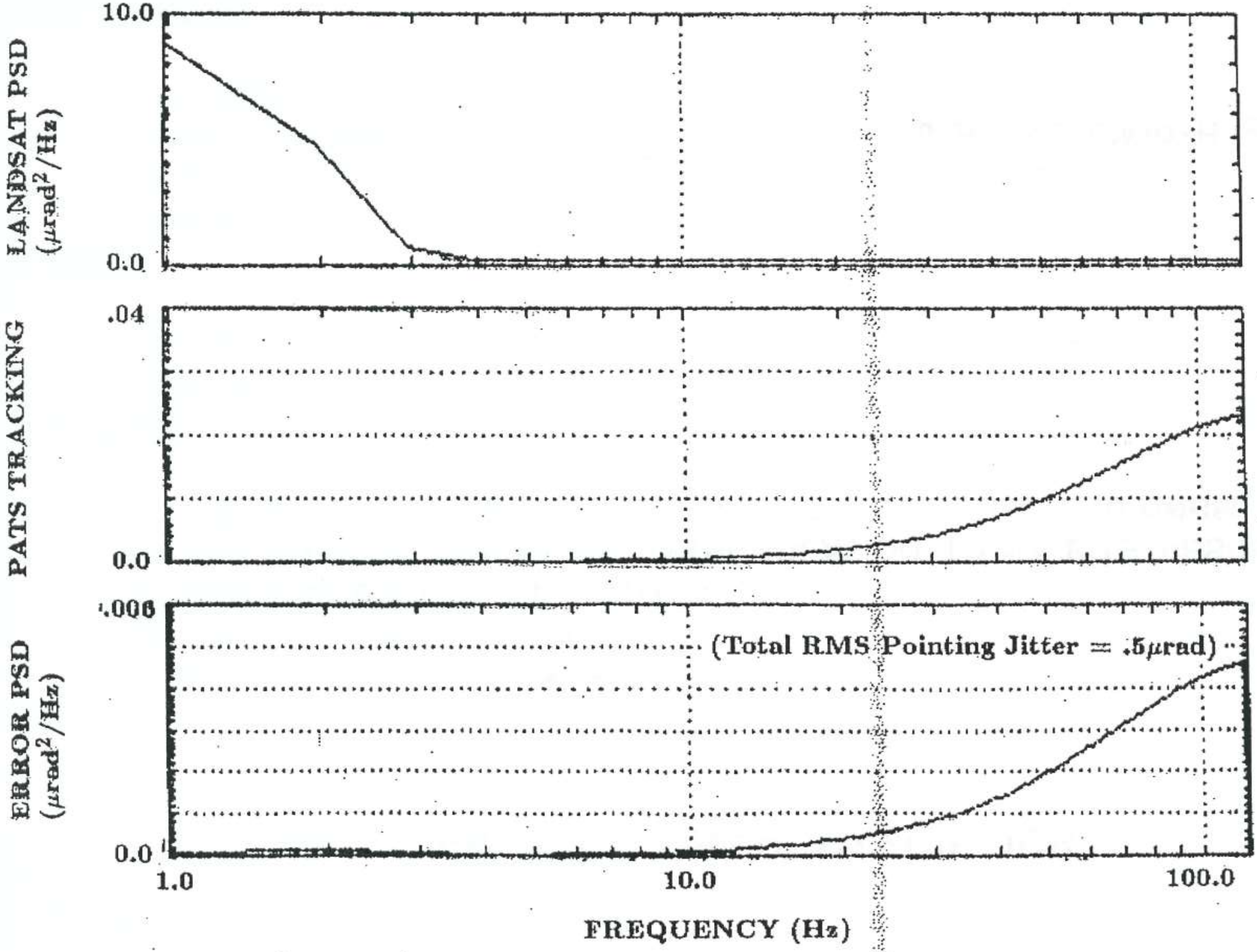
- QAPD
- ± 0.5 MR CAPTURE FIELD
- 2 GALVANOMETERS FOR FINE TRACKING (120 HZ BANDWIDTH, ± 20° STEERING)

COMMUNICATION

- DUPLEX, 50 MBPS
- QPPM, DIRECT DETECTION

PATS UNTRACKED PLATFORM JITTER

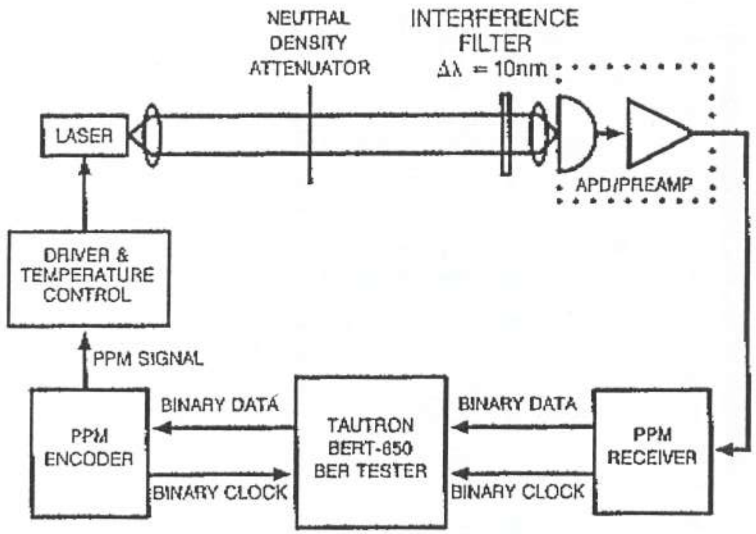
#4



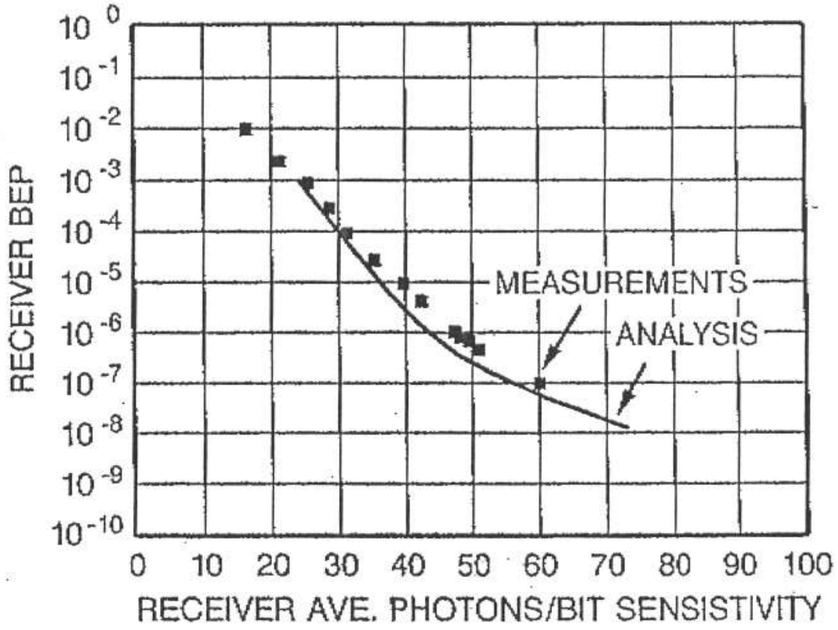
DIRECT DIRECTION RECEIVER SENSITIVITY

— M = 4 PPM —

Pulse Position Modulation



SYSTEM BLOCK DIAGRAM



- 48 DETECTED PHOTONS/BIT AT 10^{-6} BEP
- AUTONOMOUS SLOT AND SYMBOL CLOCK RECOVERY
- NEGLIGIBLE BACKGROUND, EXT. RATIO
- APD GAIN OPTIMIZED FOR 10^{-6} BEP
- TRANSIMPEDANCE GaAs FET PREAMP

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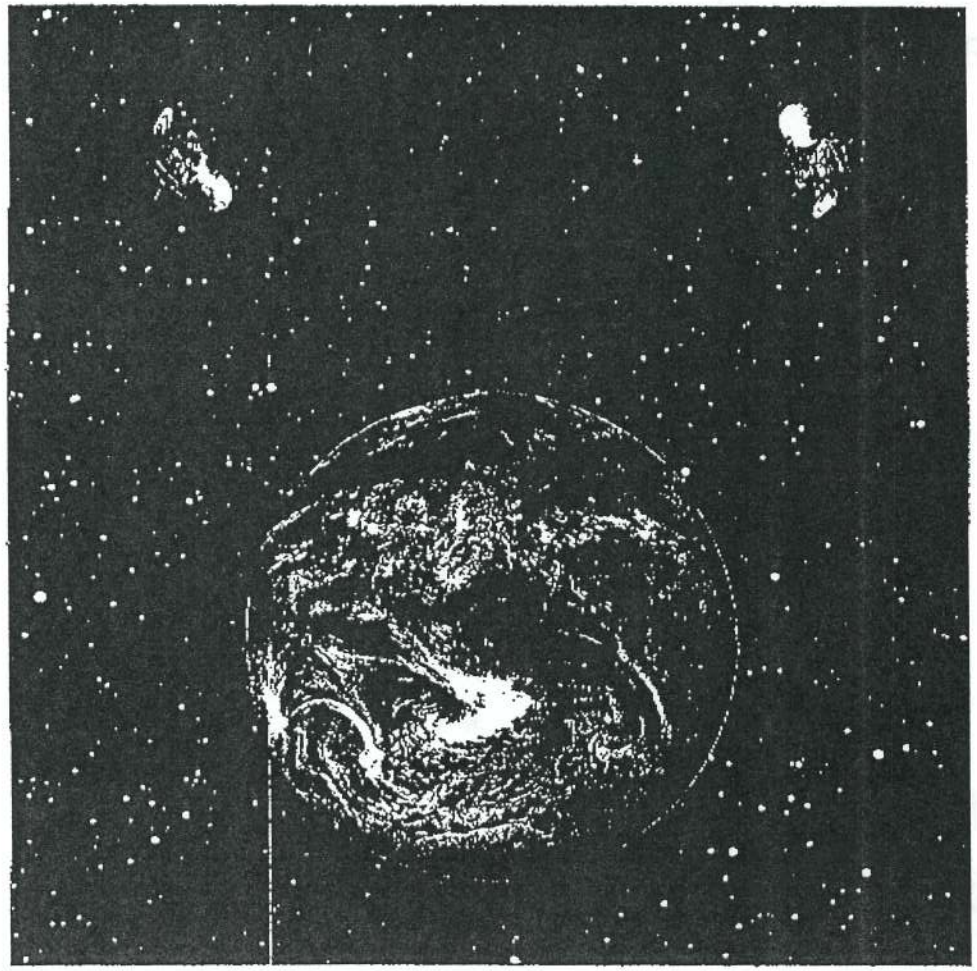
Flight Systems Development and Demonstration Program

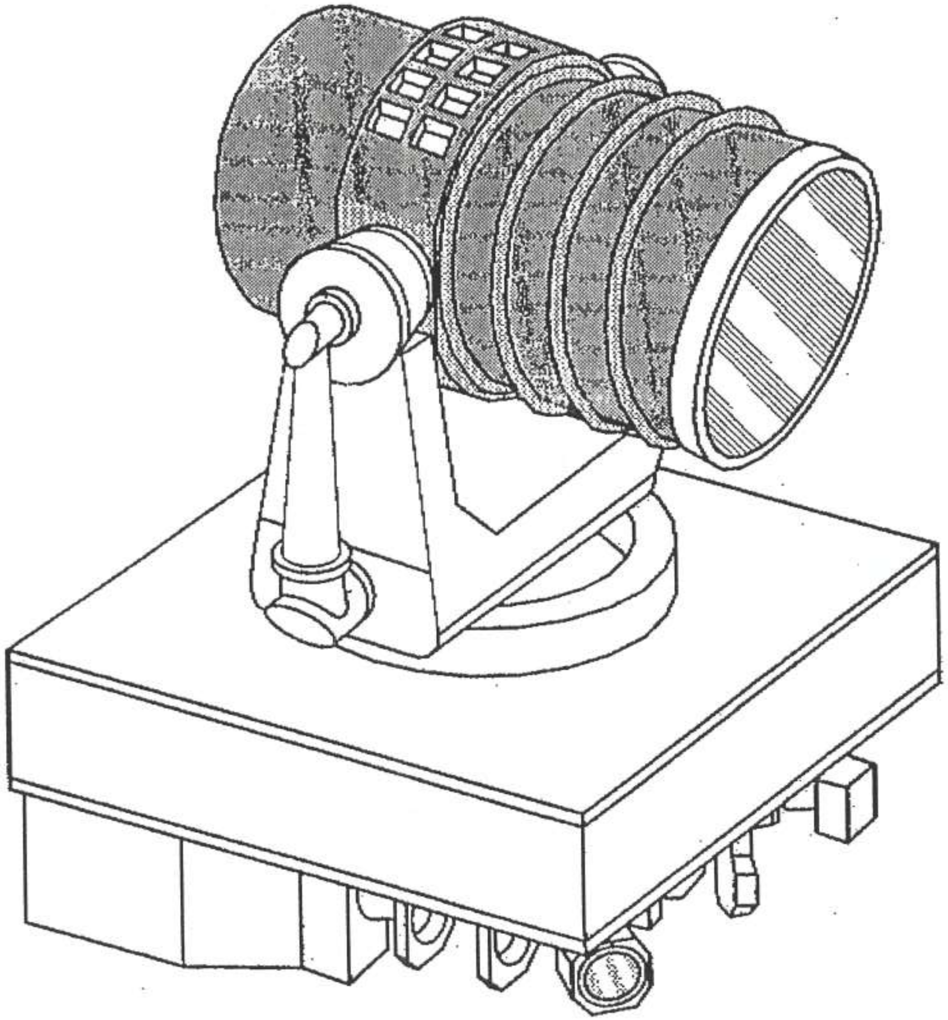


Free Space Optical Communication

Data Rate:	650 MBPS, Duplex
Data Quality:	10^{-6} BEP, Uncoded
Laser Type:	Semiconductor, Al GaAs
Modulation:	4 Slot PPM
Receiver:	Direct Detection
Telescope:	8 Inch Dia
Range:	21,000 Km
Weight:	< 250 lbs
Power:	< 200 Watts

System Requirements

SYSTEM CONCEPT



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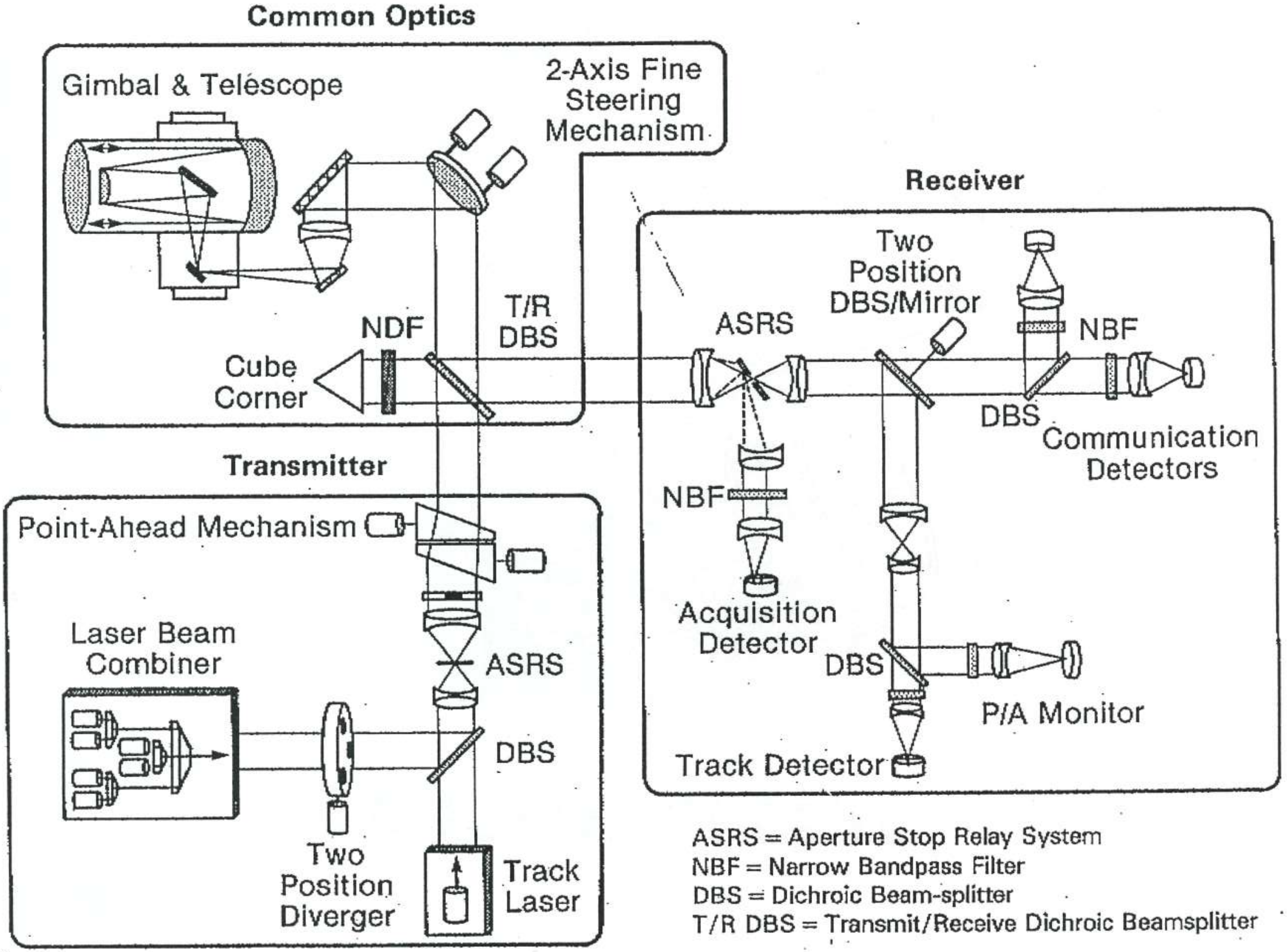
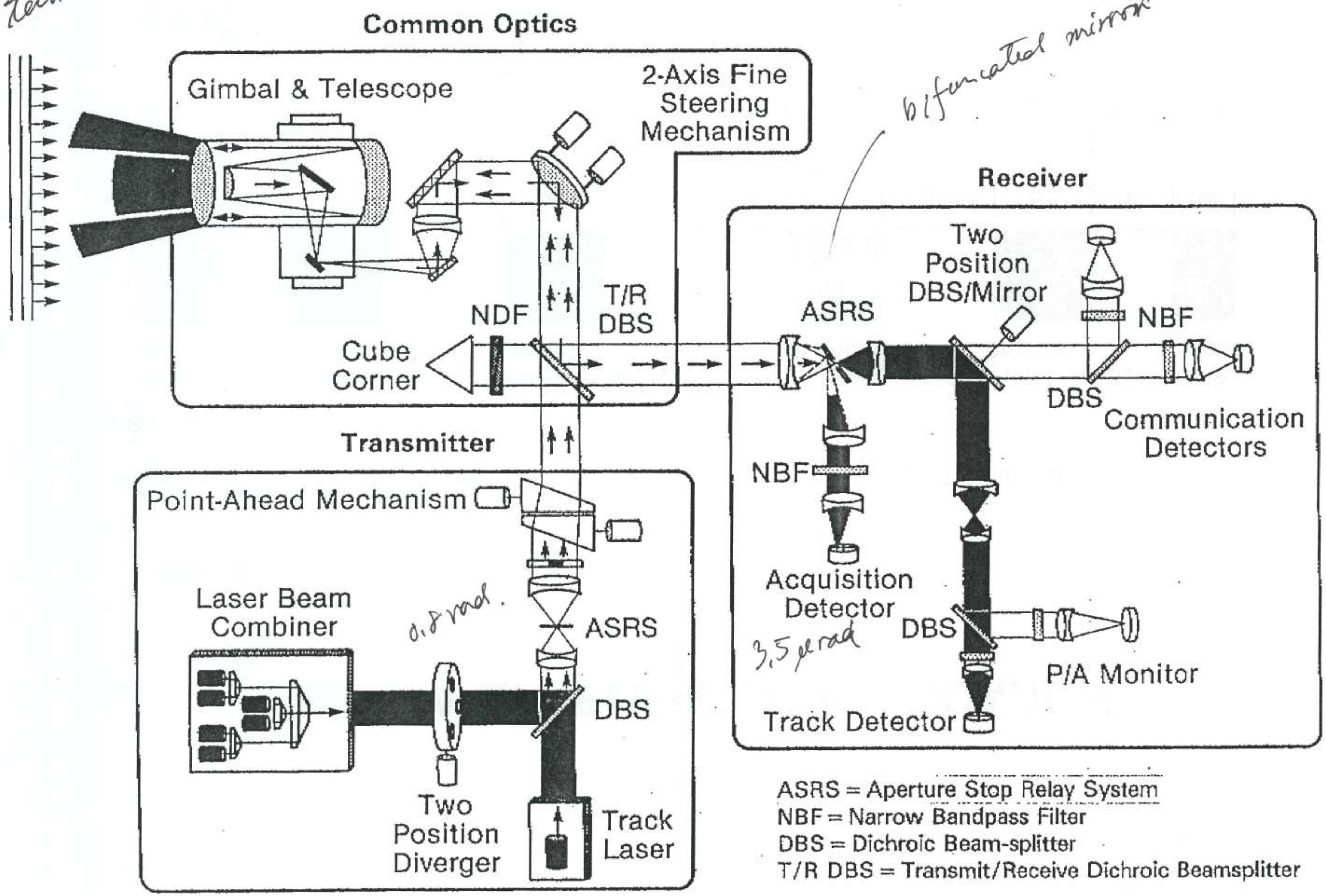
SYSTEM DIAGRAM



ASRS = Aperture Stop Relay System
NBF = Narrow Bandpass Filter
DBS = Dichroic Beam-splitter
T/R DBS = Transmit/Receive Dichroic Beamsplitter

ACQUISITION PROTOCAL

cooperating terminal



bifurcated mirror

0.8 rad.

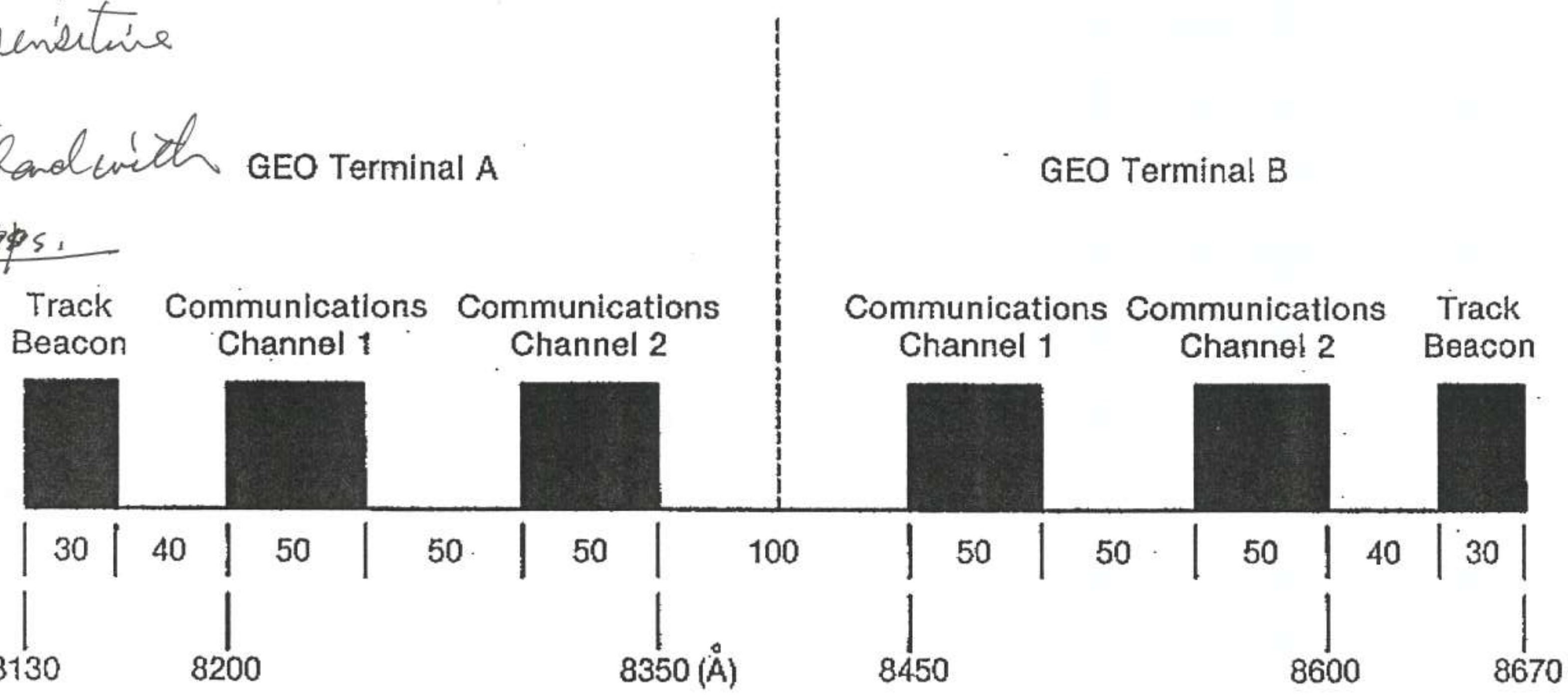
3.5 μrad

ASRS = Aperture Stop Relay System
NBF = Narrow Bandpass Filter
DBS = Dichroic Beam-splitter
T/R DBS = Transmit/Receive Dichroic Beamsplitter

SYSTEM WAVELENGTH ALLOCATION

- 400 Mpsを出すには.
power LD.
modulation 難い.

- Receiver
Si-APD sensitive
speed
gain bandwidth
600 Mbps.



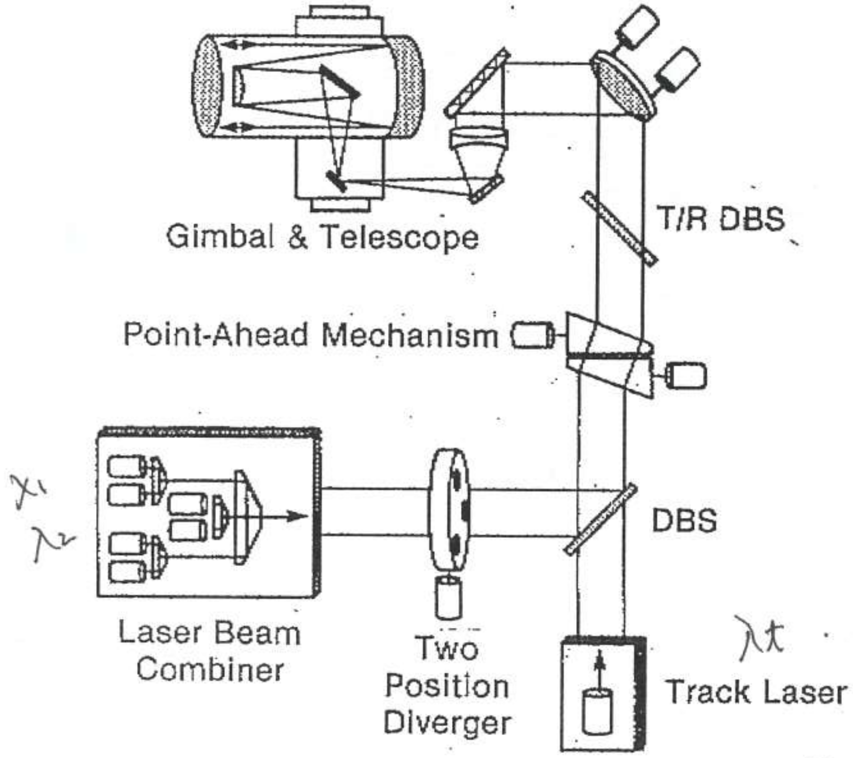
- 出来ないか
simple な
system で
[illegible].

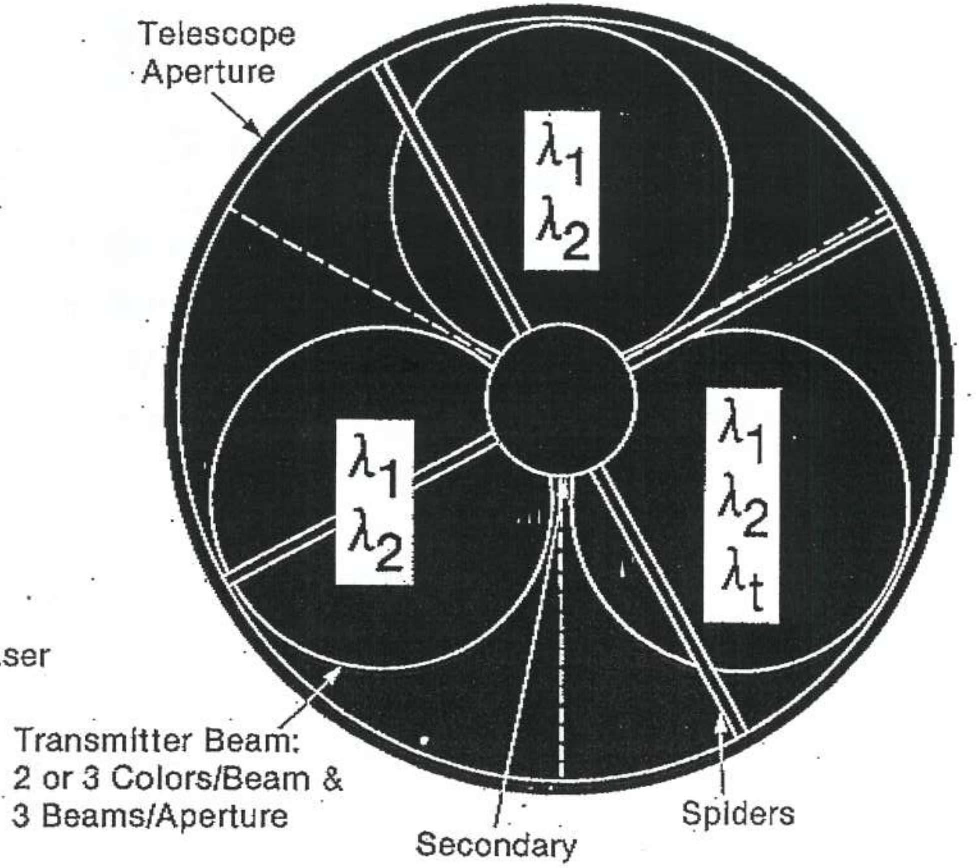
- CAT
- down link
OK
- up link, aperture averaging,
[illegible].

polarization, isolation, dichroical.

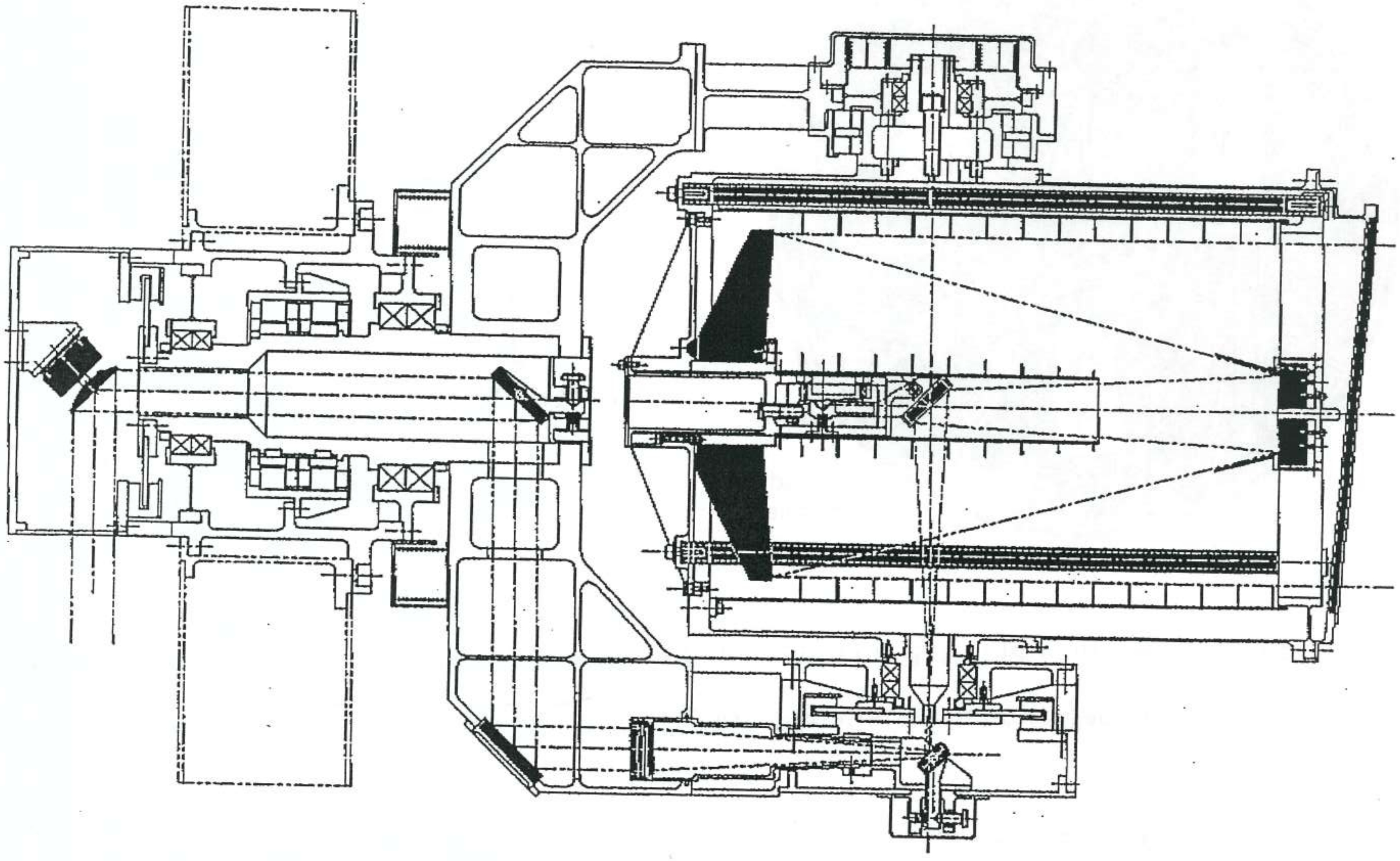
TRANSMITTER CONFIGURATION

- The Laser Beam Combiner is a Hybrid of Spatial & Dichroic Techniques
- This Reduces the Performance Requirements on Both the Pointing System & the Laser Wavelength Stability





GIMBALED TELESCOPE



STRAY LIGHT CONTROL

received power level
10^{-9} watt.
10^{-10} isolation が必要.

Two Types of Stray Light

- Internal Backscatter From Lasers
- External Solar and Earth Background

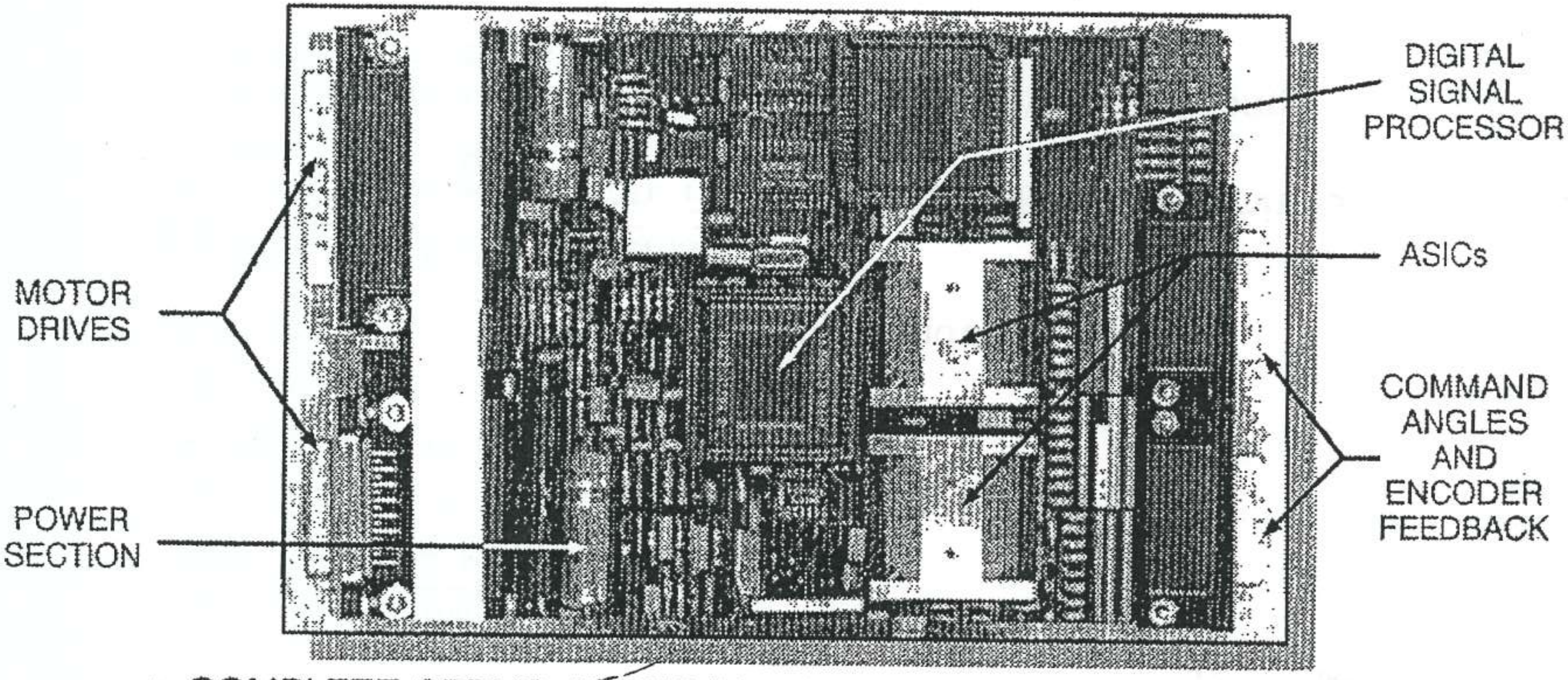
Control is Achieved By

- Field Stops — Reduce Field of View
- Aperture Stops — Reduce Scattering Area
- Baffles — Reduce Direct Input
- Optical Blacks — Reduce Reflectivity
- Spectral Filters — Reduce Spectral Bandwidth

Aperture Stop Relay Systems (ASRS)

- Prevent Transmitted Light From Striking Walls of Transmit Path (Transmit ASRS)
- Prevent Light Reflected From Walls of Receive Path From Reaching Detectors (Receive ASRS)

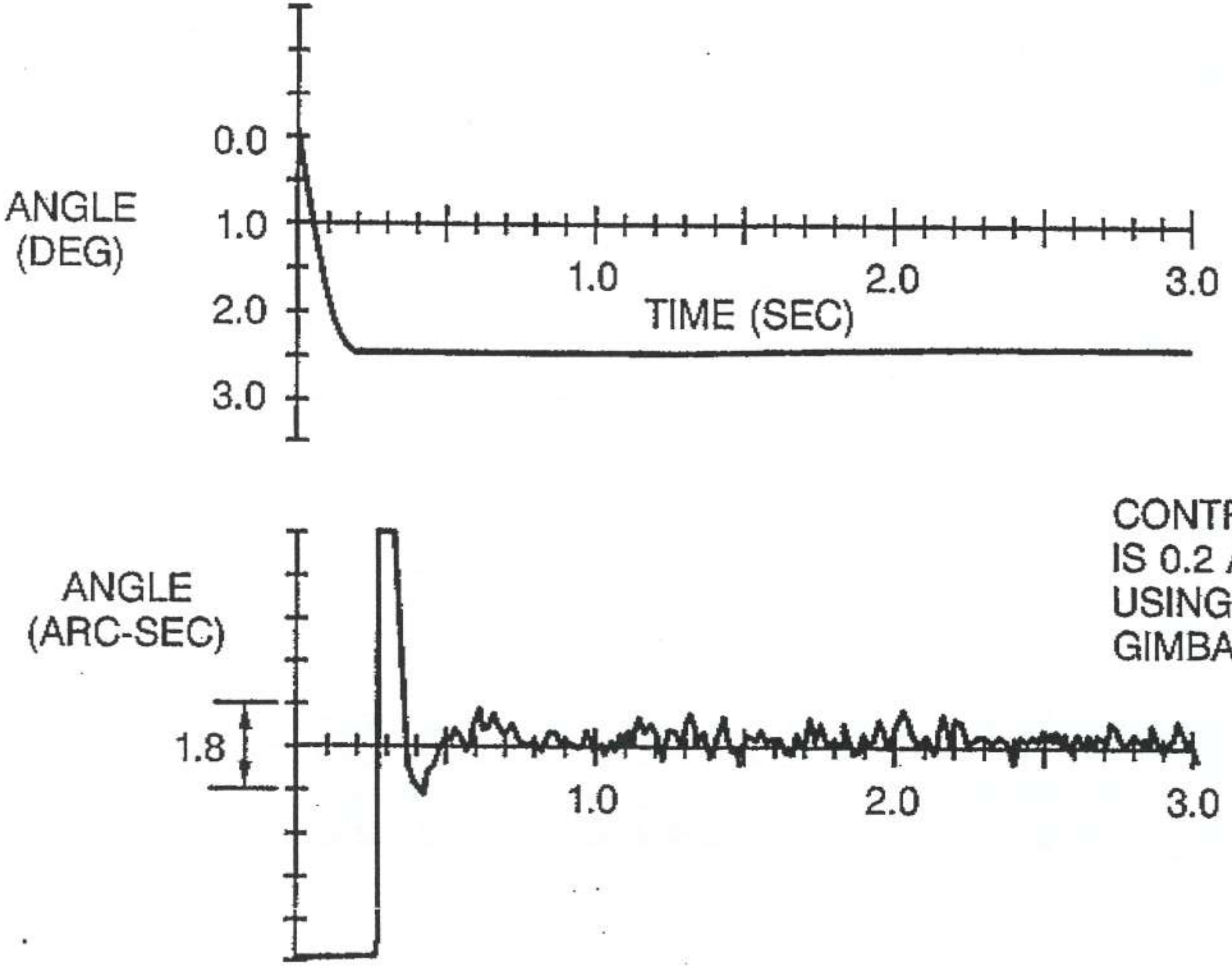
DUAL DIGITAL SERVO CONTROLLER



- COMPLETE SERVO CONTROL FOR 2 AXES
- RESOLUTION 0.3 ARC SECONDS
- IMPLEMENTS COORDINATE TRANSFORMATIONS, KALMAN FILTERING, AND OPTIMAL CONTROL ALGORITHMS
- 3 SEMI-CUSTOM ASICS
- 4 X 6 INCH BOARD, 3.7 WATTS DISSIPATION (EXC. MOTOR POWER)
- 15:1 SIZE REDUCTION, 10:1 POWER REDUCTION

8359.16 BD63.

CONTROLLER PERFORMANCE
- RESPONSE TO 2.5° INPUT STEP -



CONTROL PRECISION
IS 0.2 ARC-SEC
USING 1-AXIS
GIMBAL SIMULATOR

B350.004

LASER COMMUNICATION TRANSCEIVER (LCT) FOR SPACE STATION FREEDOM

OBJECTIVES

CONDUCT A COMPREHENSIVE SET OF IN-ORBIT TESTS TO:

- VERIFY SYSTEM PERFORMANCE
- VALIDATE ANALYTICAL MODELS
- DEMONSTRATE TECHNOLOGY MATURITY
- ESTABLISH CONFIDENCE LEVEL NEEDED FOR TRANSITION TO OPERATIONAL SYSTEMS

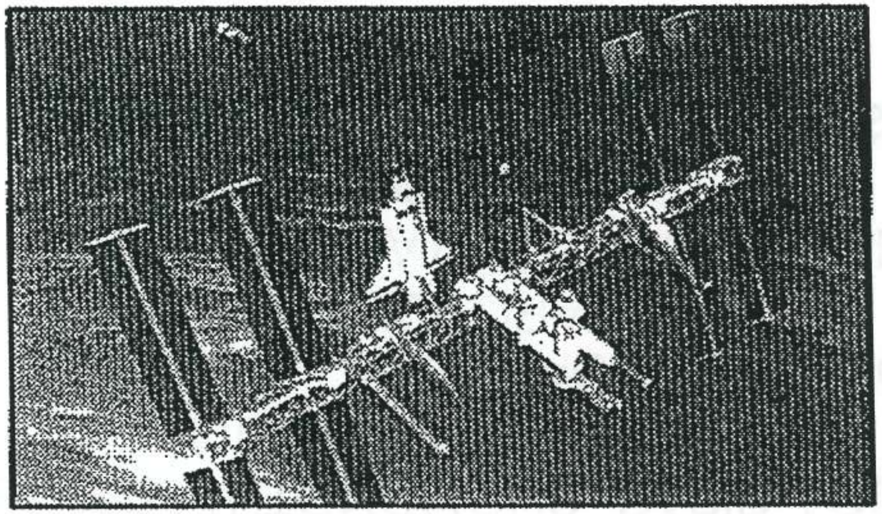
APPROACH

- DESIGN/BUILD, HIGH PERFORMANCE OPTICAL COM TRANSCEIVER FOR LOW EARTH ORBIT MISSION (SSF)
- SYSTEM DESIGN TO BE BASED ON LEO-TO-GEO COM LINK PERFORMANCE REQUIREMENTS

DRIVERS:
(1) AUTONOMOUS, RAPID ACQUISITION (10-60 SEC)
(2) HIGH ACCURACY POINTING (SUB-MICRORADIAN)
(3) HIGH DATA RATE COMMUNICATIONS (300-1200 MBPS)
(4) SMALL, LOW POWER DISSIPATION (225#, 200W)

Tx&Rx capability

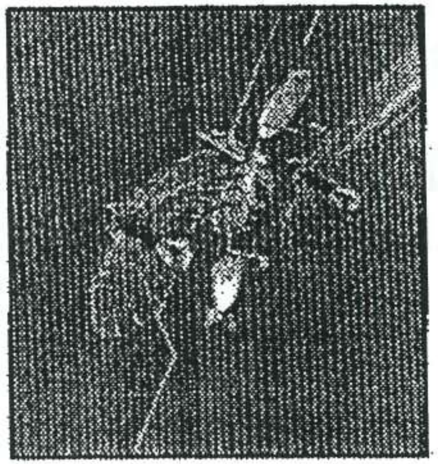
SPACE STATION LASER COMMUNICATION TRANCEIVER

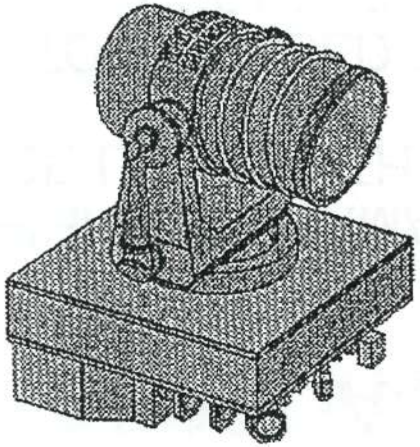


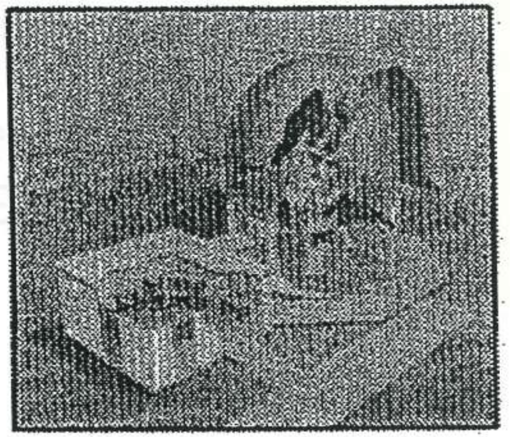
TDRS

300 .301

GEO-LEO







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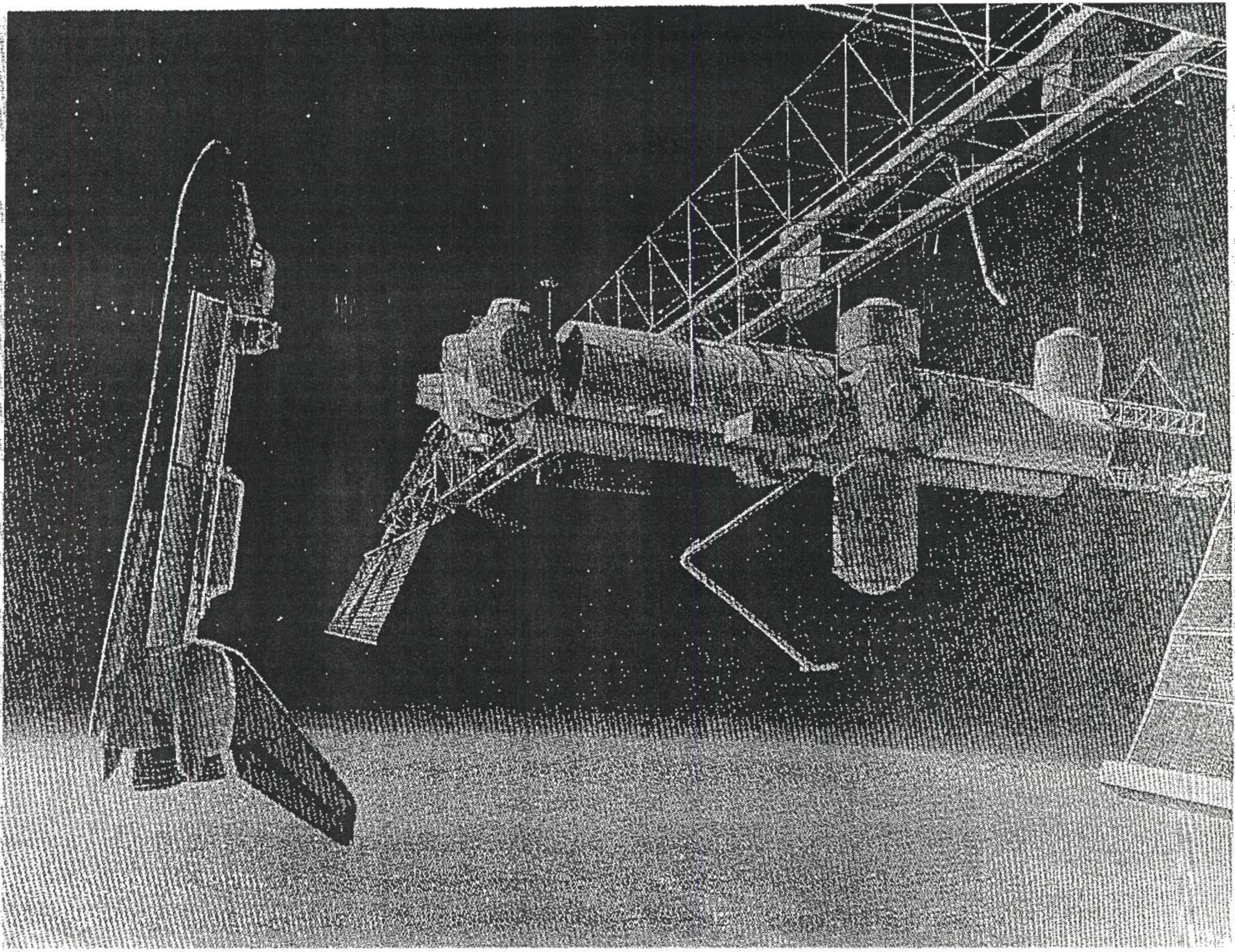


LCT ON-ORBIT TESTS

— PHASE I: LEO-TO-GROUND —

- CONDUCT FULL SET OF ACQUISITION, TRACKING, POINTING, AND COMMUNICATION TESTS WITH 2 OR MORE LASER GROUND STATIONS
  (1) 48" RESEARCH FACILITY AT GSFC
  (2) REMOTE GROUND STATION AT TBD LOCATION
- GSFC FACILITY LIMITED TO LOW ELEVATION "PASSES"; REMOTE STATION TO SERVE AS PRIME GROUND STATION
- CONSERVATIVE DESIGN APPROACH FOR LEO-TO-GROUND TESTS
  (1) DESIGN, ANALYSIS BASED ON LOW EVALUATION GSFC "PASSES" (5-15°)
  (2) REMOTE GROUND STATION WILL OPERATE WITH 20-90° ELEVATION ANGLES AND WILL HAVE 10-20 DB MORE LINK MARGIN
- PHASE B STUDY WILL IDENTIFY CANDIDATE REMOTE GROUND STATIONS. SELECTION DEFERRED UNTIL PHASE C/D

D350.005

LCT BASELINE DESIGN

HARDWARE:

- 8" GIMBALLED CASSEGRAIN TELESCOPE WITH COUDE' OPTICS
  - PROVIDES HEMISPHERICAL COVERAGE AND COARSE TRACKING
- INTEGRATED ELECTRO-OPTICS ASSEMBLY
  - TRACK/COM LASERS
  - ACQ/TRACK/COM DETECTORS
  - PRECISION TRACKING, P/A AND ACQ/TRACK/COM OPTO-MECHANICAL MECHANISMS
- SPECTRA DIODE LAB'S 5400 SERIES LASERS
  - CONSERVATIVE, LOW-RISK AVG. AND PEAK POWER REQUIREMENTS
  - LOW-RISK, LOOSE WAVELENGTH STABILITY REQUIREMENTS
- POINTING, ACQUISITION AND CONTROL SYSTEM
  - HI- AND LOW-BANDWIDTH NESTED-SERVO LOOP
  - HEMISPHERICAL FIELD-OF-REGARD AND 1 KHz HIGH-RESOLUTION RESPONSE

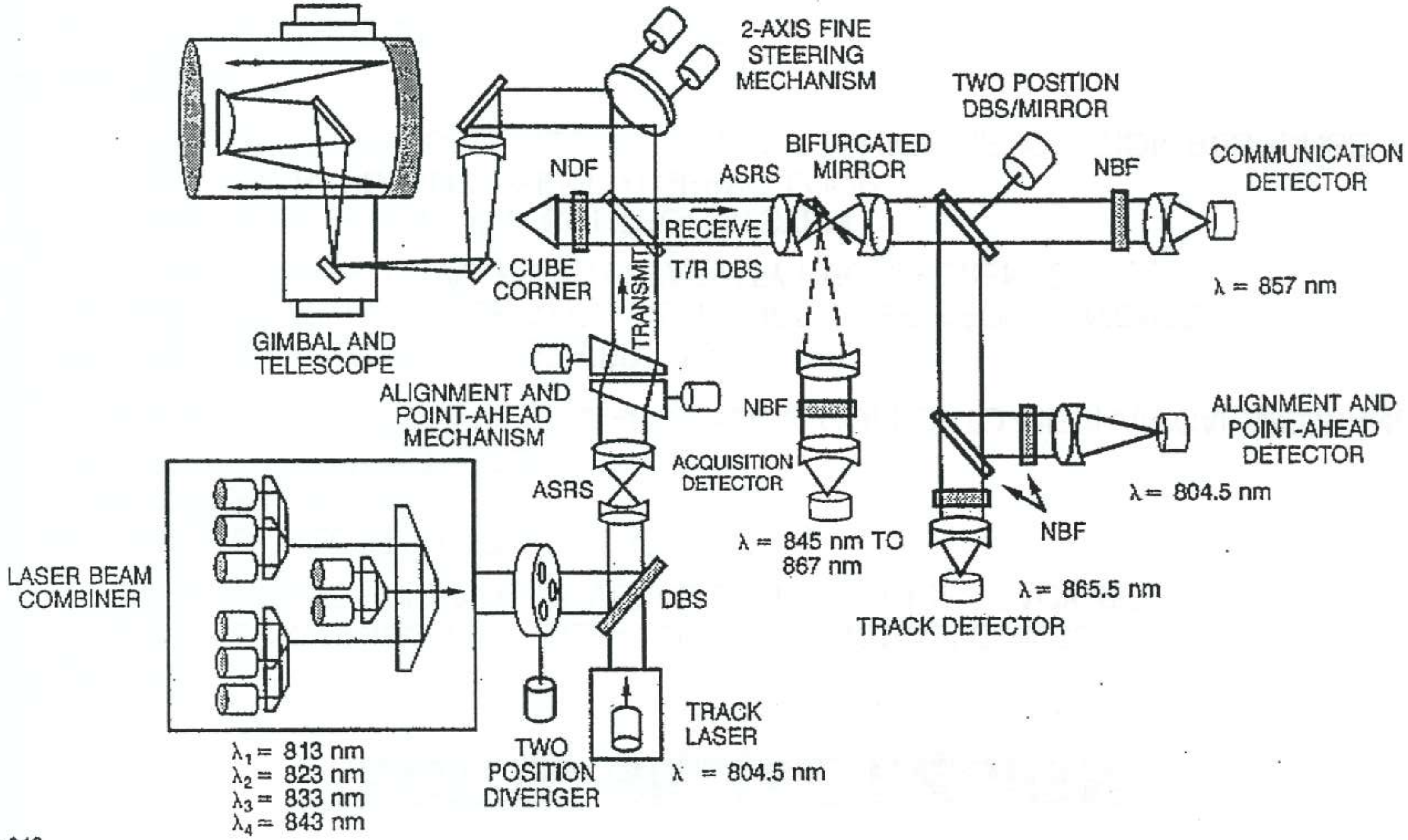
OPERATIONS:

- 300 MBPS BUILDING-BLOCK DATA RULES
- ROBUST ACQUISITION IMPLEMENTATION
  - 3.5 MILLIRAD (0.2 DEGREES) FOV
  - CONSERVATIVE, MULTI-STAGE PROCESS
  - FLEXIBLE HARDWARE WILL ACCOMMODATE CHANGES

D350.006

LCT FLIGHT TERMINAL OPTICAL DIAGRAM

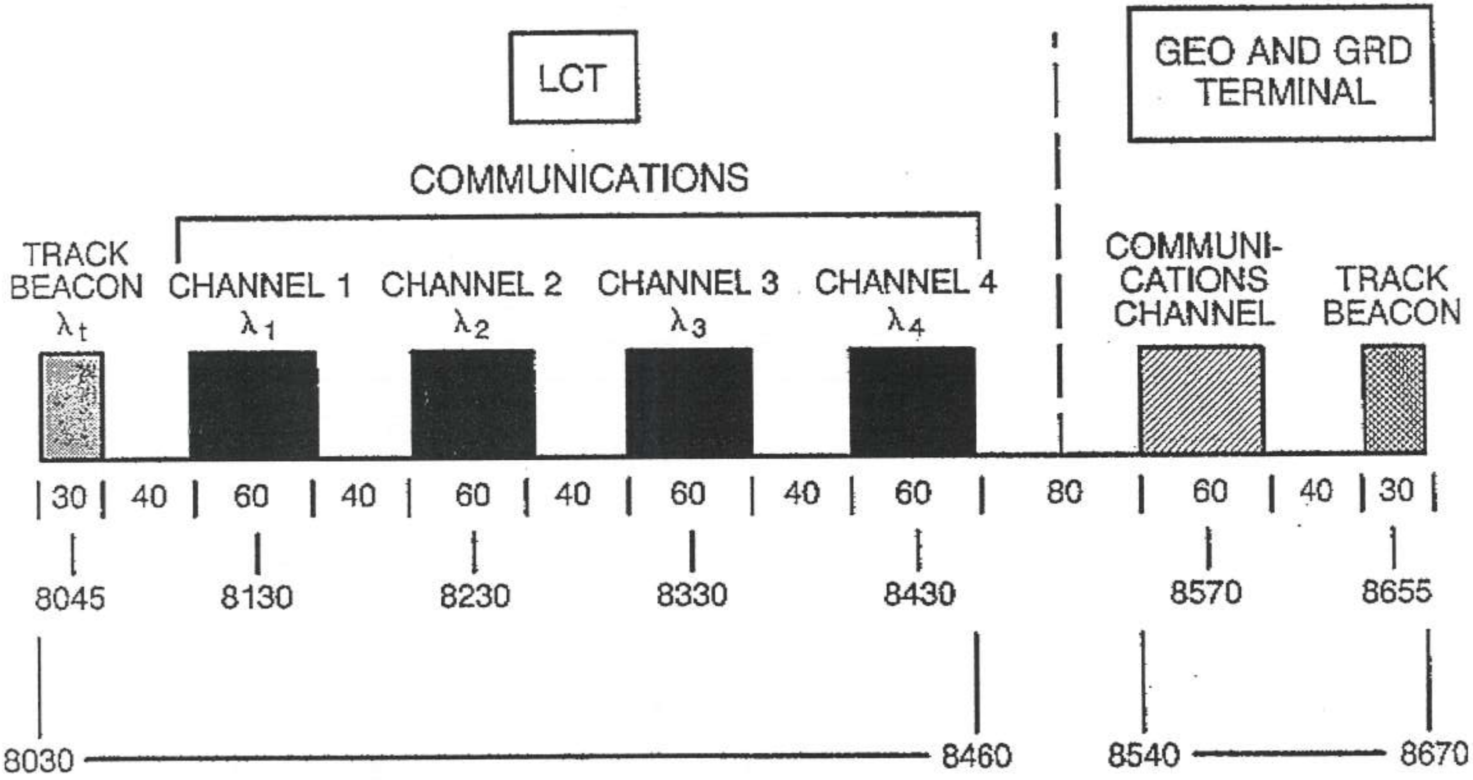
- LCT OPTICAL DESIGN BASED ON FSDD HERITAGE



D350.018

LCT TRANSMITTER WAVELENGTH ALLOCATION

- 4 CHANNELS OF 300 MBPS EACH ARE BUILDING BLOCKS FROM THE FSDD DESIGN
- THE SYSTEM DATA RATE CAN ADAPT TO ANY COMBINATION OF 300 MBPS



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LCT-GT ACQUISITION AND TRACKING LINK BUDGETS

- ROBUST 6 DB MARGIN ON WORST-CASE ACQUISITION LINK

PARAMETERS	ACQ	COARSE TRACK	LCT FINE TRACKS GT	GT FINE TRACKS LCT
AVG XMIT POWER (mW)	1460	1460	1460	15
OPTICAL WAVELENGTH (nm)	855	855	855	855
XMIT FWHM BEAM WIDTH (mrad)	0.1	0.1	0.1	0.01
RECEIVER APERTURE DIAMETER (cm)	20.3	20.3	20.3	102
REQ POWER DENSITY AT DETECTOR (W/m^2)	1.2E-09	1.08E-11	1.4E-10	5.54E-12
ELEVATION ANGLE (DEGREE)	5	5	5	5
MEAN EARTH RADIUS (m)	6370000	6370000	6370000	6370000
SLANT RANGE (km)	2076.97	2076.97	2076.97	2076.97
VISIBILITY CONDITION (km)	5	5	5	5
BACKGROUND	SUN-LIT	SUN-LIT	SUN-LIT	SUN-LIT
AVG. XMIT POWER (dbW)	1.64	1.64	1.64	-18.24
XMITR ANTENNA GAIN	90.41	90.41	90.41	110.41
XMIT LOSSES	-2.00	-2.00	-4.00	-4.00
RANGE LOSS	-269.69	-269.69	-269.69	-269.69
ATMOSPHERIC LOSS	-28.90	-28.90	-28.90	-28.90
RCVR ANTENNA GAIN	117.45	117.45	117.45	131.48
RCVR LOSSES	-4.00	-4.00	-4.00	-4.00
RCVR EDGE OF COVERAGE	-3.00	-3.00	NA	NA
RECEIVED AVG. POWER AT DETECTOR (dbW)	-98.08	-98.08	-97.08	-82.94
REQUIRED AVG. POWER AT DETECTOR (dbW) (COARSE TRACKS ASSUME NEB = 100Hz, NEA = 2 urad; FINE TRACKS ASSUME NEB = 1 kHz, NEA - 0.5 urad)	-104.11	-124.56	-113.44	-113.44
LINK MARGIN	6.02	26.48	16.35	30.50

D350.008

LCT-GT COMMUNICATION LINK BUDGET

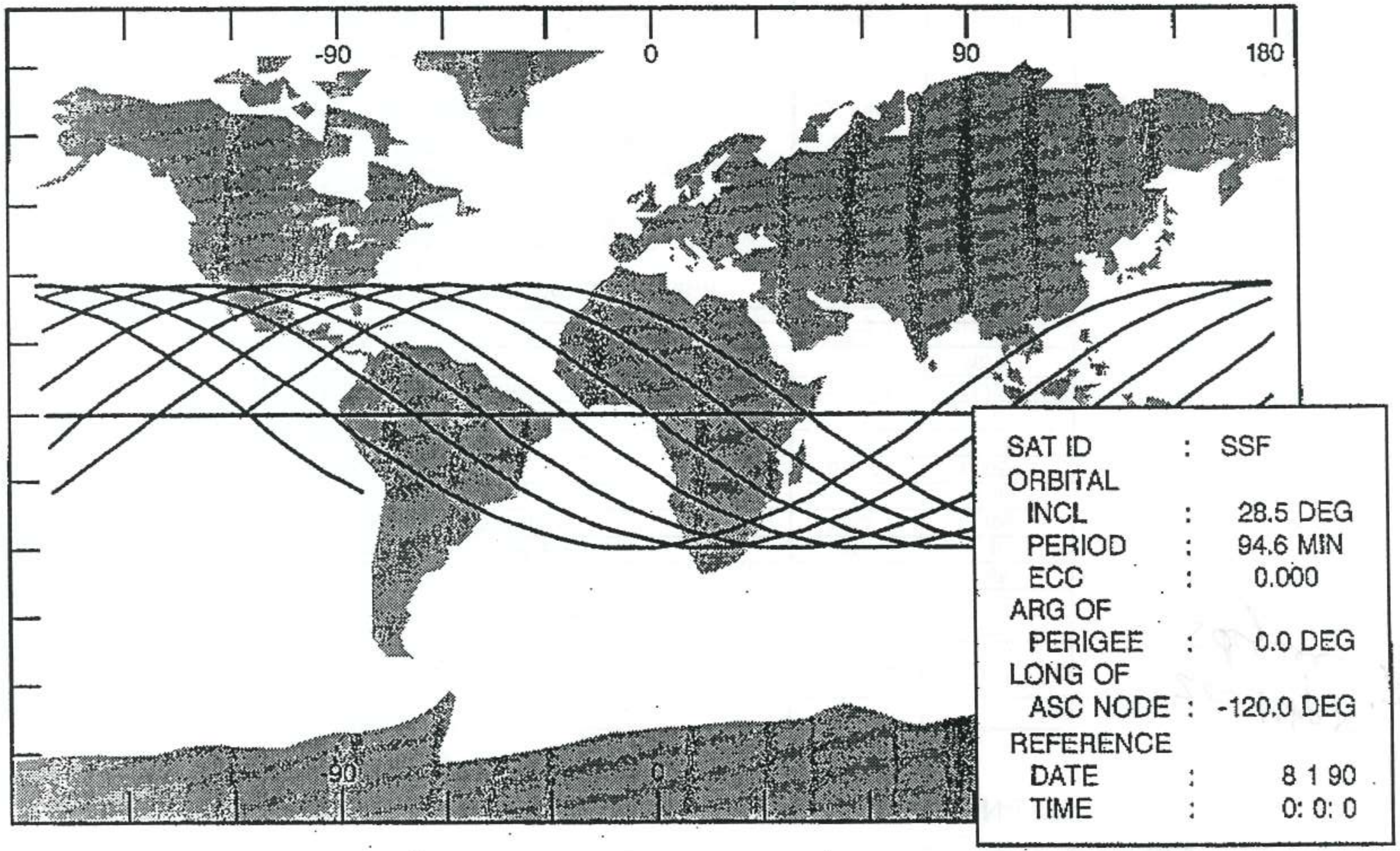
- ROBUST 6 DB MARGIN ON WORST-CASE DOWN-LINK
- O DB MARGIN ON LOW-ELEVATION UPLINK

PARAMETERS		
MULTIPLE LINKS	UPLINK	DOWNLINK
SINGLE CHANNEL DATA RATE (Mbps)	300	300
AVERAGE LASER OUTPUT POWER (mW)	200	50
LASER PEAK POWER (mW)	800	200
RECEIVER SENSITIVITY (PHOTONS/BIT)	65	65
FWHM XMIT BEAM WIDTH (urad)	100	10
RECEIVER APERTURE (cm)	20.3	102
MPPM ORDER	4	4
DATA QUALITY (BER)	1.00E-06	1.00E-06
OPTICAL WAVELENGTH (nm)	855	855
ELEVATION ANGLE (DEGREE)	5	5
MEAN EARTH RADIUS (m)	6370000	6370000
SLANT RANGE (km)	2076.97	2076.97
VISIBILITY CONDITION (km)	25.3	5

LASER MODULE OUTPUT AVG POWER (dBW)	-6.99	-13.01
TRANSMITTER GAIN	90.41	110.41
OPTICS ATTENUATION (REFLECTANCE/XMITTANCE)	-0.40	-0.40
TRUNCATION AND OTHER OPTICS LOSSES	-3.00	-2.23
PHASE ABERATION (WAVELENGTH/10 rms SURFACE DEVIATION)	-1.71	-1.71
POINTING LOSS (RMS JITTER = .5 urad)	0.00	-0.10
RANGE LOSS (WAVELENGTH/4piR)^ 2	-269.69	-269.69
ATMOSPHERIC LOSS (dB)	-6.28	-28.90
RECEIVER GAIN	117.45	131.48
RECEIVER OBSCURATION LOSS (GAMMA = 0.3)	-0.40	-0.40
RECEIVER FILTER LOSS	-2.00	-2.00
RECEIVER OPTICS ATTENUATION (REFLECTANCE/TRANSMITTANCE)	-0.40	-0.40
RECEIVED POWER AT APD	-83.00	-76.96
POWER REQUIRED FOR COMMUNICATION	-83.44	-83.44
LINK MARGIN (dB)	0.43	6.48

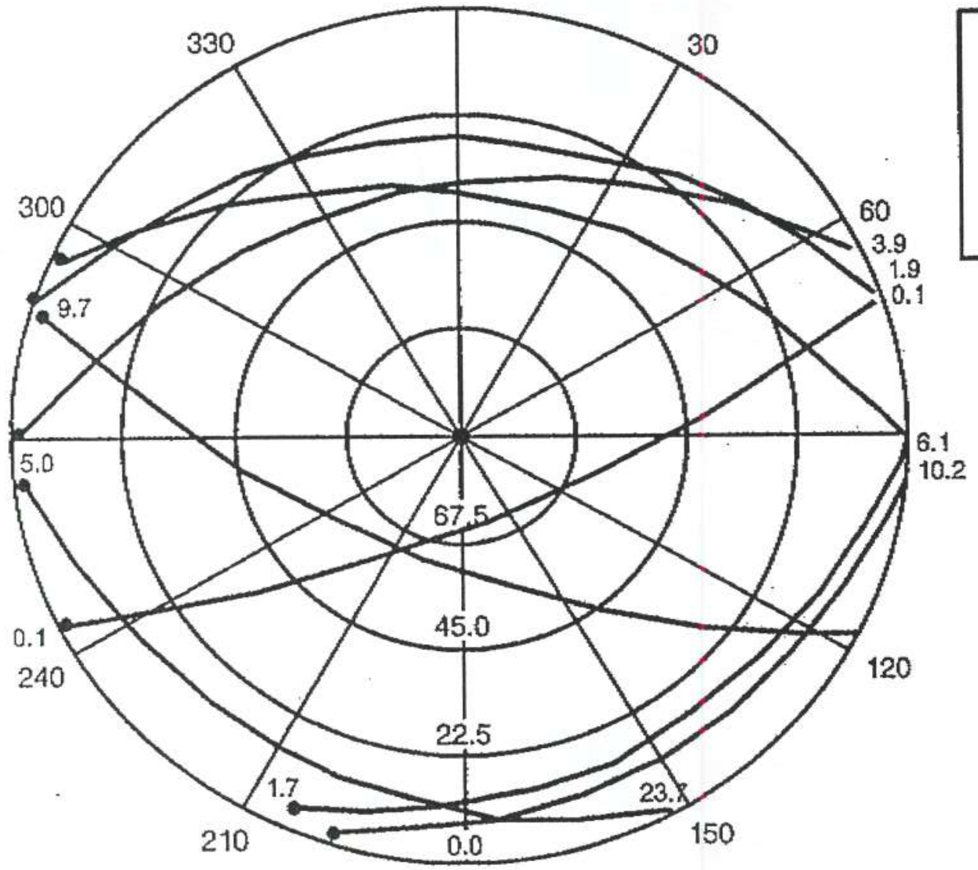
200 Mbps, Elevation
5 degree

SSF 12 HOUR GROUND TRACE SUMMARY



SAT ID : SSF
ORBITAL
INCL : 28.5 DEG
PERIOD : 94.6 MIN
ECC : 0.000
ARG OF
PERIGEE : 0.0 DEG
LONG OF
ASC NODE : -120.0 DEG
REFERENCE
DATE : 8 1 90
TIME : 0: 0: 0

MAUI AZMIMUTH VS. ELEVATION: 500 KM ALTITUDE

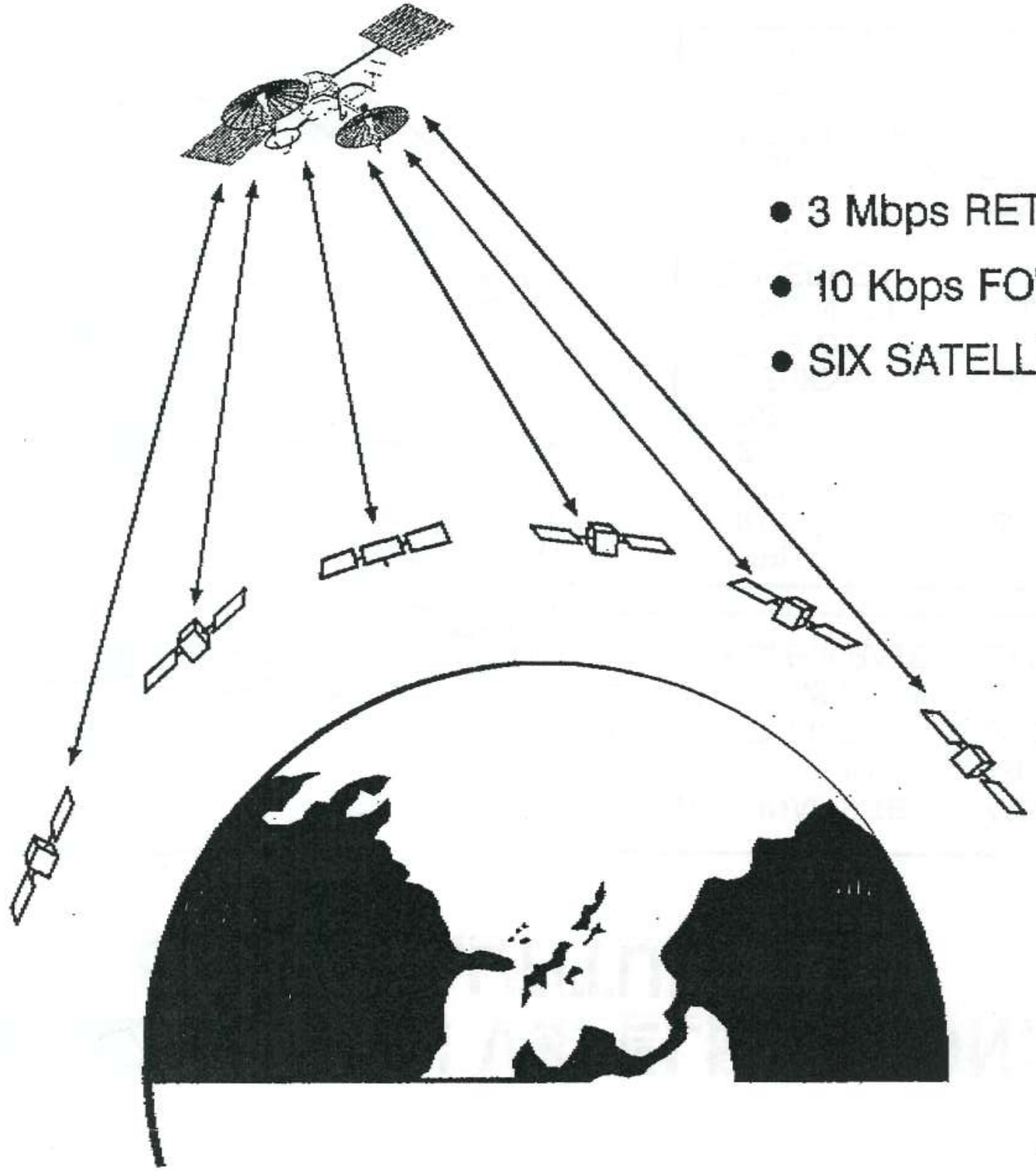


TERMINAL SITE: MAUI
SATELLITE ID: SSF
START TIME: 0: 2: 0
STOP TIME: 23:49: 0
MAX SLEW RATE: 2.7158 DG/S

ORBITAL
INCL : 28.5 DEG
PERIOD : 94.6 MIN
ECC : 0.000
ARG OF
PERIGEE : 0.0 DEG
LONG OF
ASC NODE : -180.0 DEG
OBSERVER
LAT : 21.0 DEG
LONG : -166.0 DEG
ALT : 3050.0 M
REFERENCE
DATE : 8 1 90
TIME : 0: 0: 0

D350.013

MULTI-ACCESS LASER COMMUNICATION SYSTEM



- 3 Mbps RETURN LINK
- 10 Kbps FOWARD LINK
- SIX SATELLITES

E350.001

COMPARISON OF SMA VS. OMA

S-band Multi-Access.

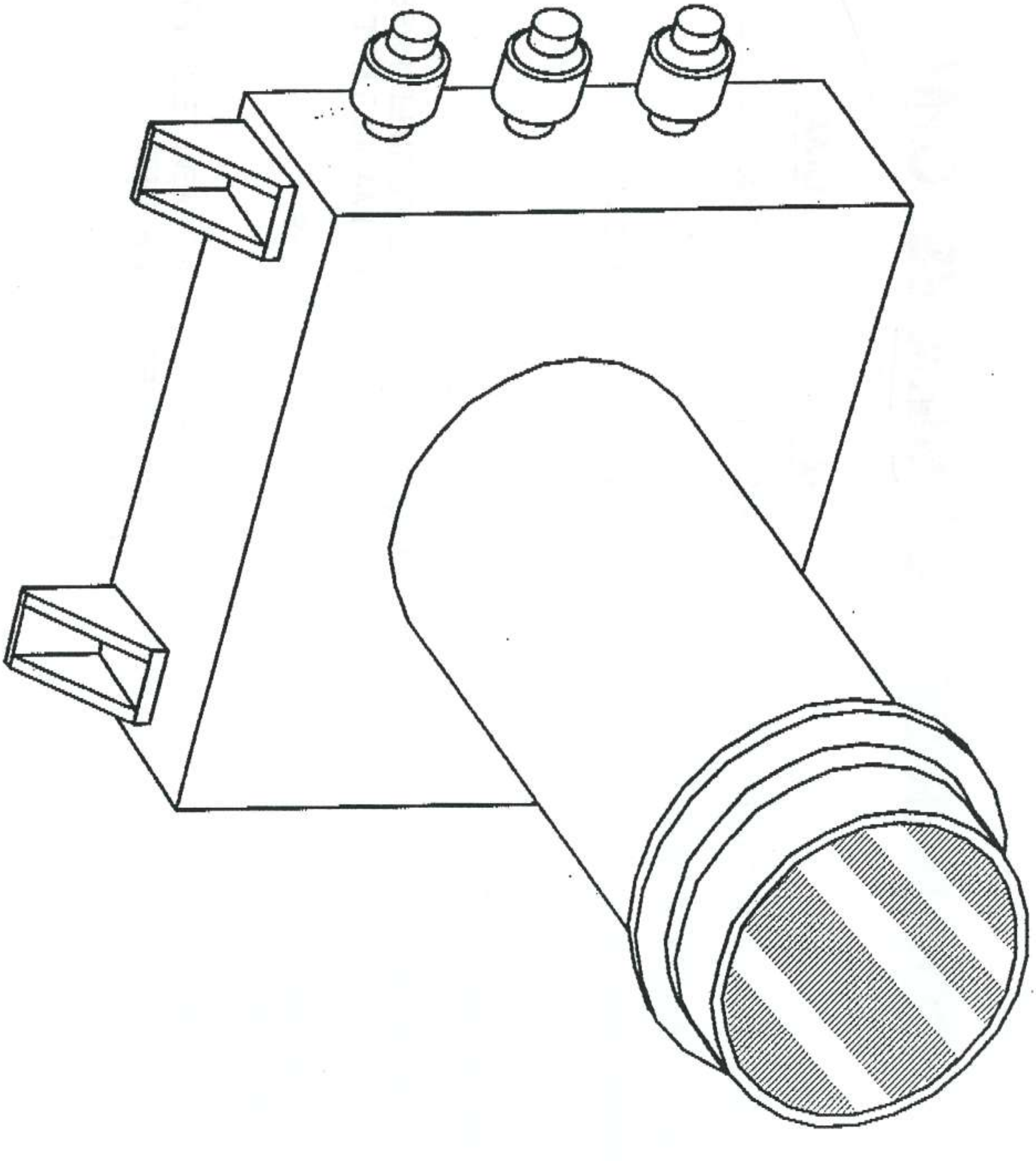
Optical Multi-Access

	SMA	OMA
REAL ESTATE (EARTH VIEWING)	13.5 X 15 FT*	0.8 SQUARE FEET
TOTAL SYSTEM WEIGHT (GEO)	504 # *	150 #
TOTAL SYSTEM POWER (GEO)	1218 W*	100 W

OTHER CONSIDERATIONS

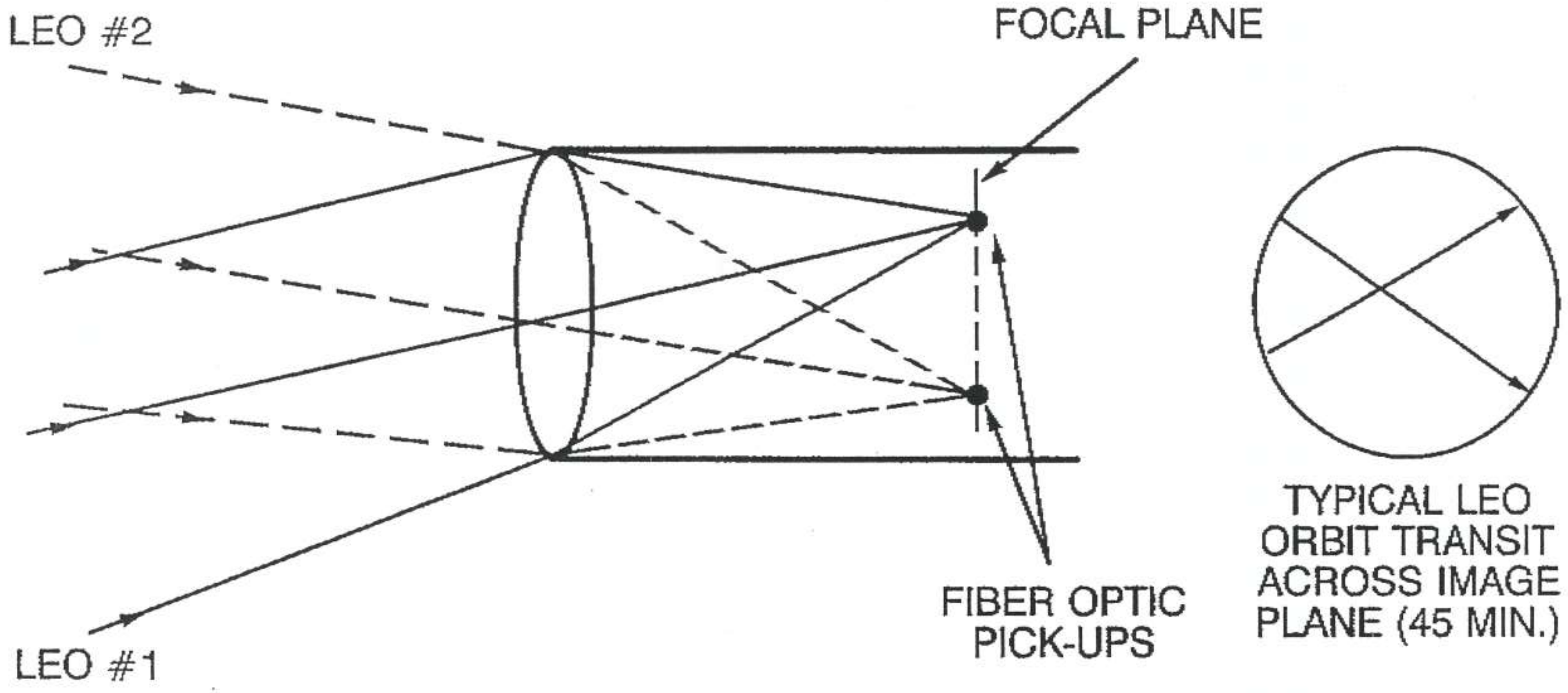
UNBOARD BEAM FORMING	COMPLEX	PERFORMED PASSIVELY BY IMAGING OPTICS
TRANSPONDER (BENT PIPE CONFIGURATION)	YES	YES
TECHNOLOGY STATUS	DEPENDENT ON SELECTED APPROACH	NO NEW TECHNOLOGY NEEDED

*LOCKHEED PH. A ATDRSS STUDY


E350.013

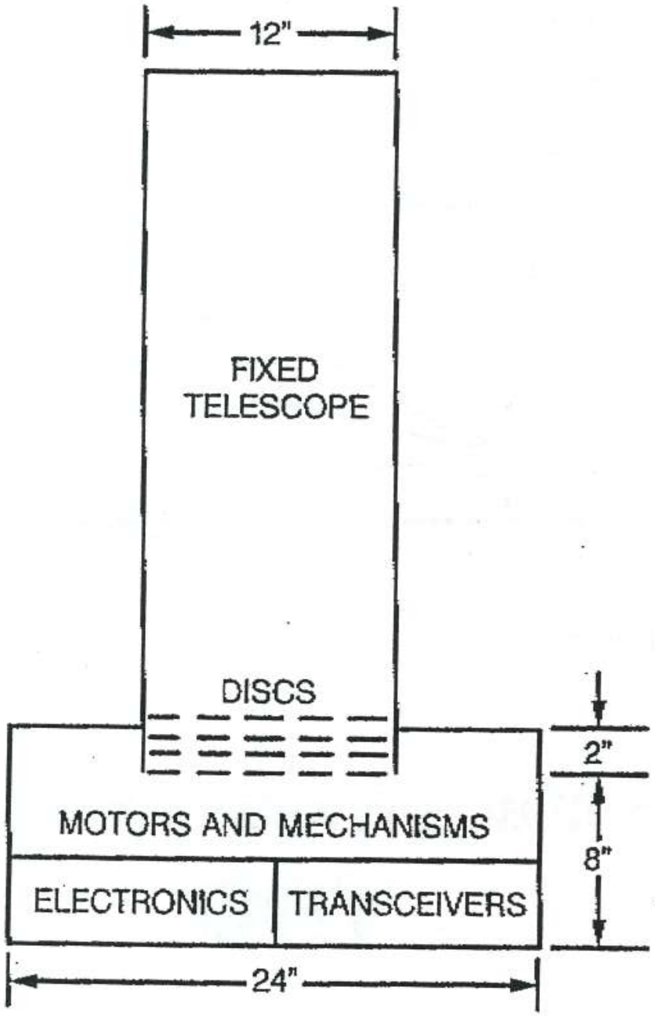
OMA

- ON BOARD BEAM FORMING -



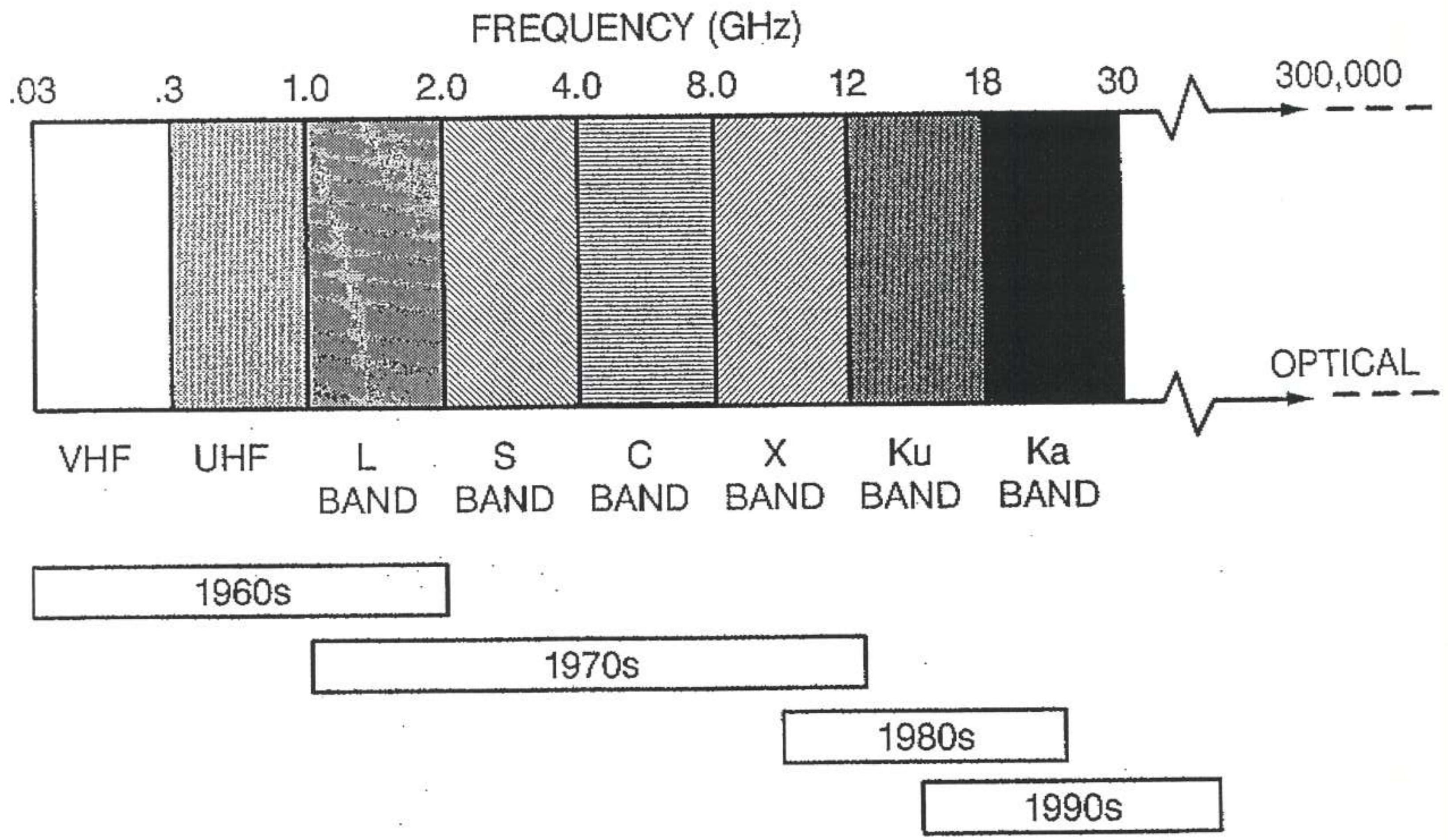
E350.011

LOCATION OF KEY SECTIONS IN MULTI-ACCESS DISC SYSTEM



D350.008

EVOLUTION OF NASA SPACE COMMUNICATION



B350.009

1-2

The European SILEX Project and other advanced concepts for optical space communications

Gotthard Oppenhaeuser
Manfred E. Wittig
Alexandru F. Popescu

ESA
ESTEC

IWOSC '90

December 6 and 7, 1990, ATR, Kyoto

european space agency
european space research and technology centre

CP/GO/2060/do

ABSTRACT

The European SILEX project and other advanced concepts for optical space communications

Authors: G. Oppenhäuser, M.Wittig, A. Popescu

European Industry, under contract of the European Space Agency ESA is developing an optical communication system allowing a two directional data transmission between spacecraft. Two terminals are being developed and built; both will be flown by 1995, one on the French earth observation spacecraft SPOT-4 in LEO orbit, the other on ESA's technology spacecraft ARTEMIS in GEO orbit. The data rate will be 16 Mbit/sec in GEO-LEO direction and 65 Mbit/sec in the LEO-GEO direction. A direct detection system will be used. As transmitter a 100 mW-cw solid state laser diode is intensity modulated by the data stream, the light is received in the counter terminal by an APD. The telescopes on both terminals have 25 cm diameter. CCD's are used as acquisition and tracking detectors. A solid state laser beacon on-board the GEO-terminal provides the required intensity for the acquisition process. For tracking purposes apart of the optical communication signal is used, avoiding such a dedicated tracking beacon. For pointing functions three mechanism are used: coarse pointing assembly with at least hemispherical range, a fine pointing system of high bandwidth with limited pointing range and an open loop operated point ahead mechanism.

In order to optimise the characteristics of future operational systems developments are ongoing aiming at an increase of the capacity and reducing the mass and size of the terminals. This goal is expected to be achieved by introducing Nd Yag lasers and heterodyne systems.

The paper will describe the activities of the European Space Agency in the area of the SILEX project and for advanced systems using NdYag lasers.

Attachment to R/GO/2256/CMM

BIOGRAPHY - G. OPPENHÄUSER

Gotthard Oppenhäuser was born in 1942 in Germany. He studied Electronics and Telecommunications at the Technical University of Darmstadt (Germany) from 1961 to 1967. Then, he joined the Research Centre of the German PTTs and as of 1969 he was member of the project team in charge of the procurement of the German/French communication satellite "Symphony".

In 1974, he became a staff member of the European Space Agency and was working as payload engineer for various communication satellites like OTS, ECS and OLYMPUS.

To-date (1990) he is payload manager of the "Data Relay and Technology Mission Programme" of the European Space Agency.

SILEX

esa

THE

SEMICONDUCTOR LASER INTERSATELLITE LINK EXPERIMENT

OF THE

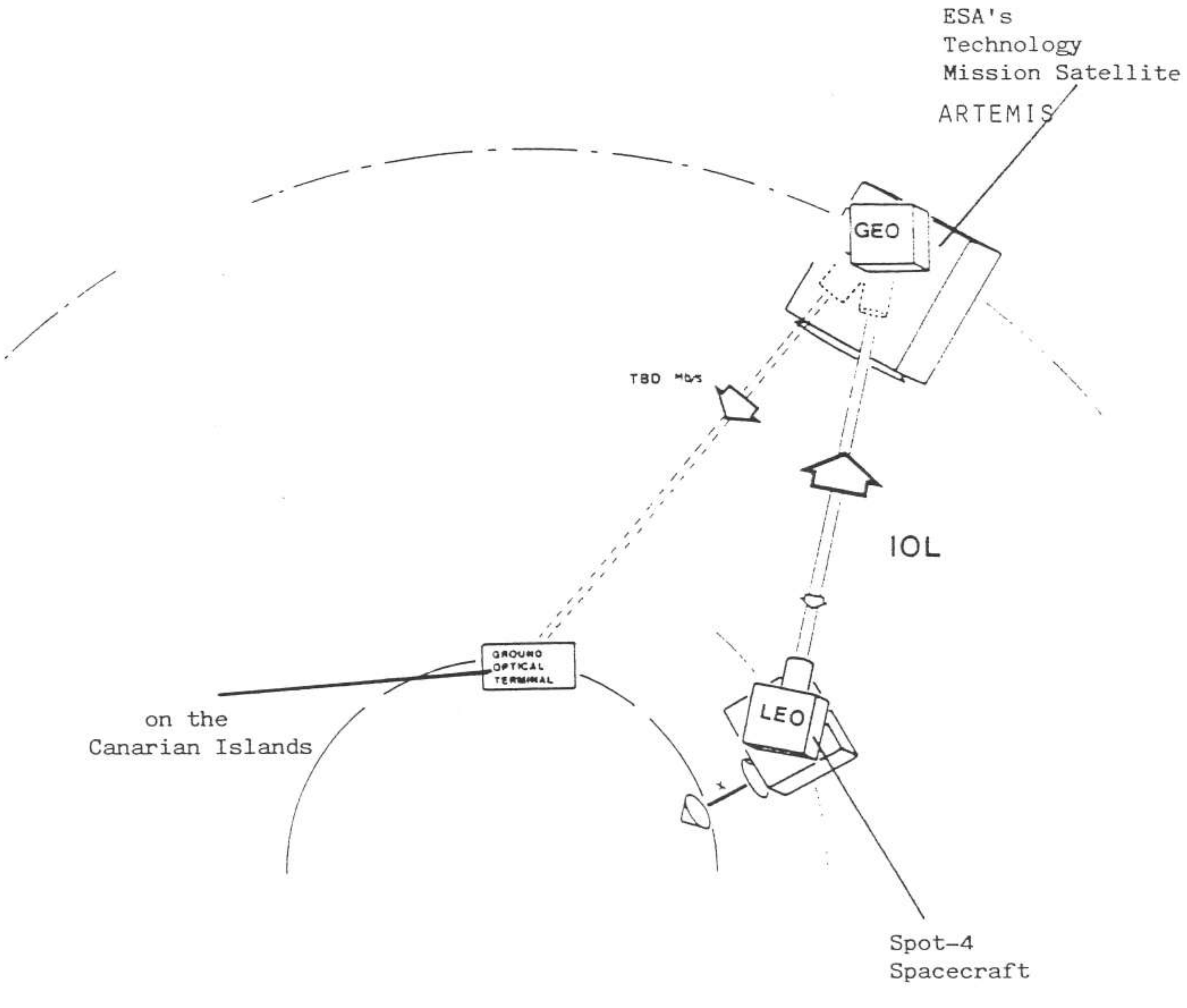
EUROPEAN SPACE AGENCY

AND OTHER ADVANCED CONCEPTS FOR OPTICAL SPACE COMMUNICATION SYSTEMS

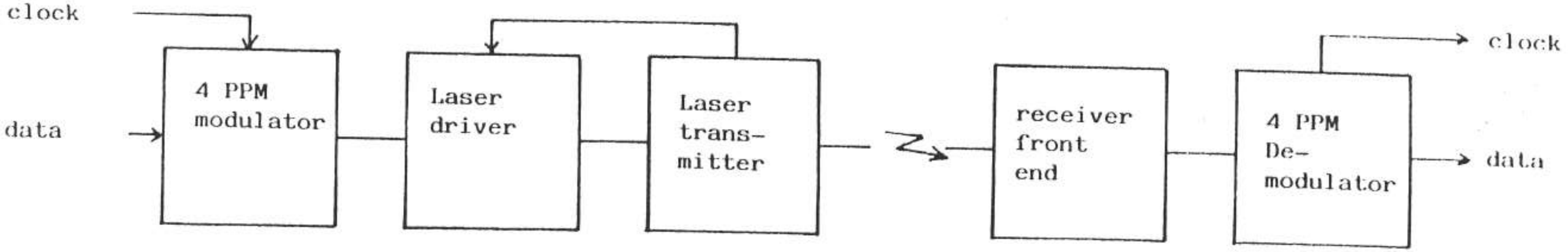
G. OPPENHÄUSER, M. WITTIG, A. POPESCU - EUROPEAN SPACE AGENCY, ESTEC, NOORDWIJK, THE NETHERLANDS

PURPOSE OF THE SILEX PROGRAMME :

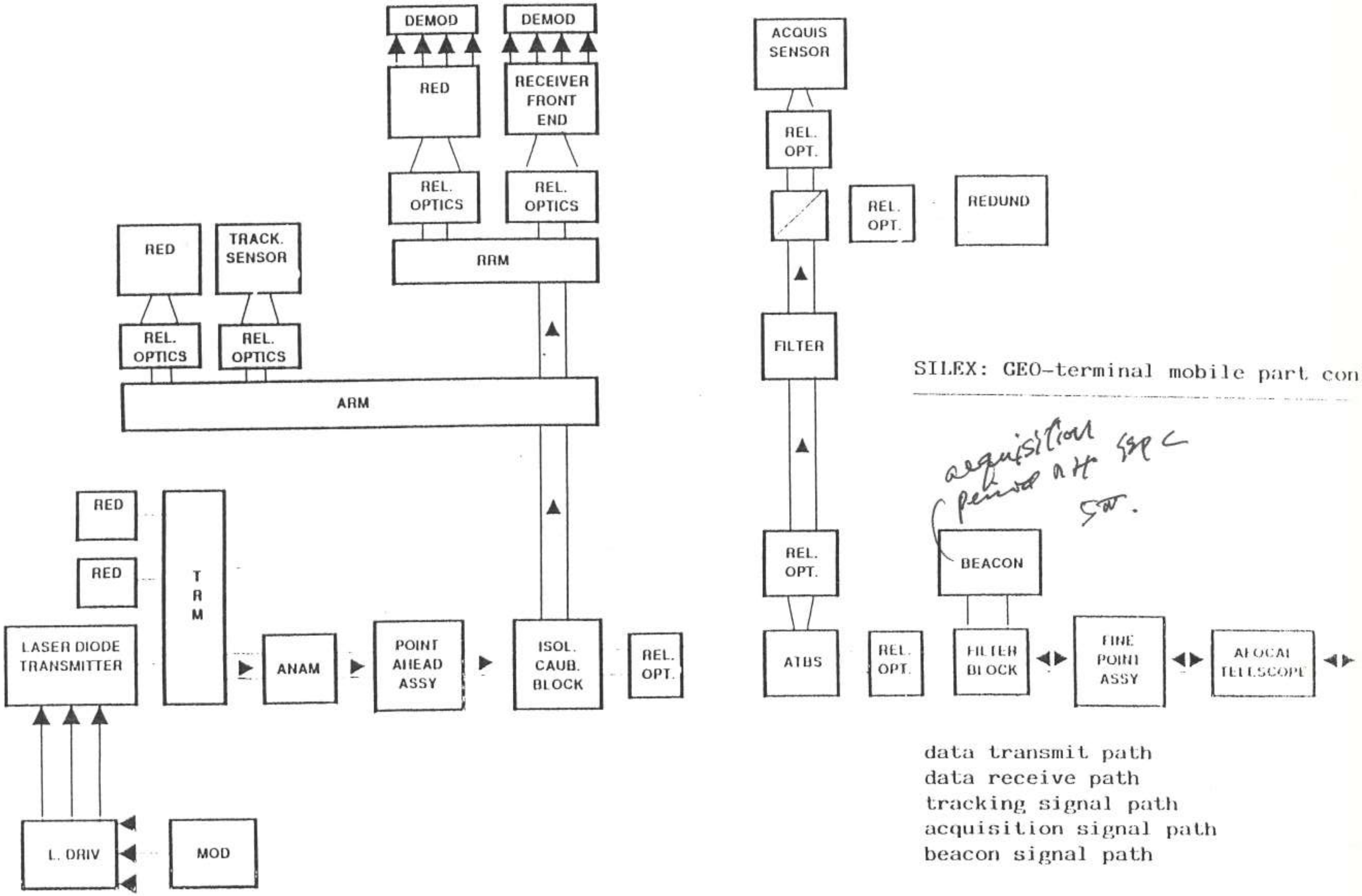
- TO DEVELOP ALL HARDWARE ELEMENTS OF THE OPTICAL TERMINALS
- TO DEVELOP OPERATIONAL PROCEDURES FOR A DATA RELAY TYPE APPLICATION
- TO DEMONSTRATE THE CAPABILITY OF OPTICAL LINKS IN SPACE BY EXPERIMENTS AND BY PRE-OPERATIONAL APPLICATIONS
- TO PREPARE THE OPERATIONAL APPLICATION IN THE FRAME OF THE EUROPEAN DATA RELAY SATELLITE SYSTEM



SILEX MISSION CONFIGURATIONS



SILEX: Simplified Block Diagramme of the Communication Subsystem

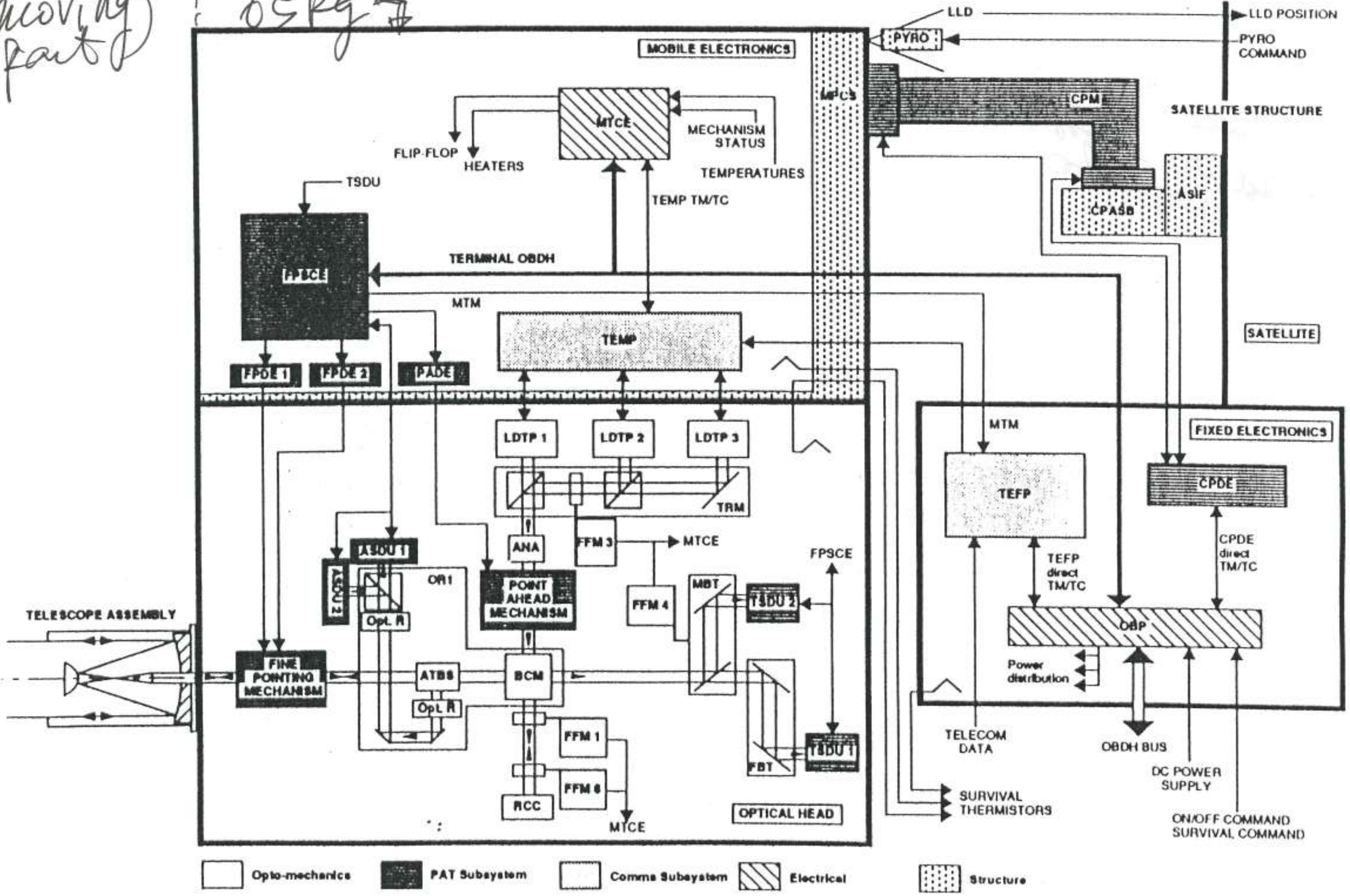


SILEX: GEO-terminal mobile part configuration

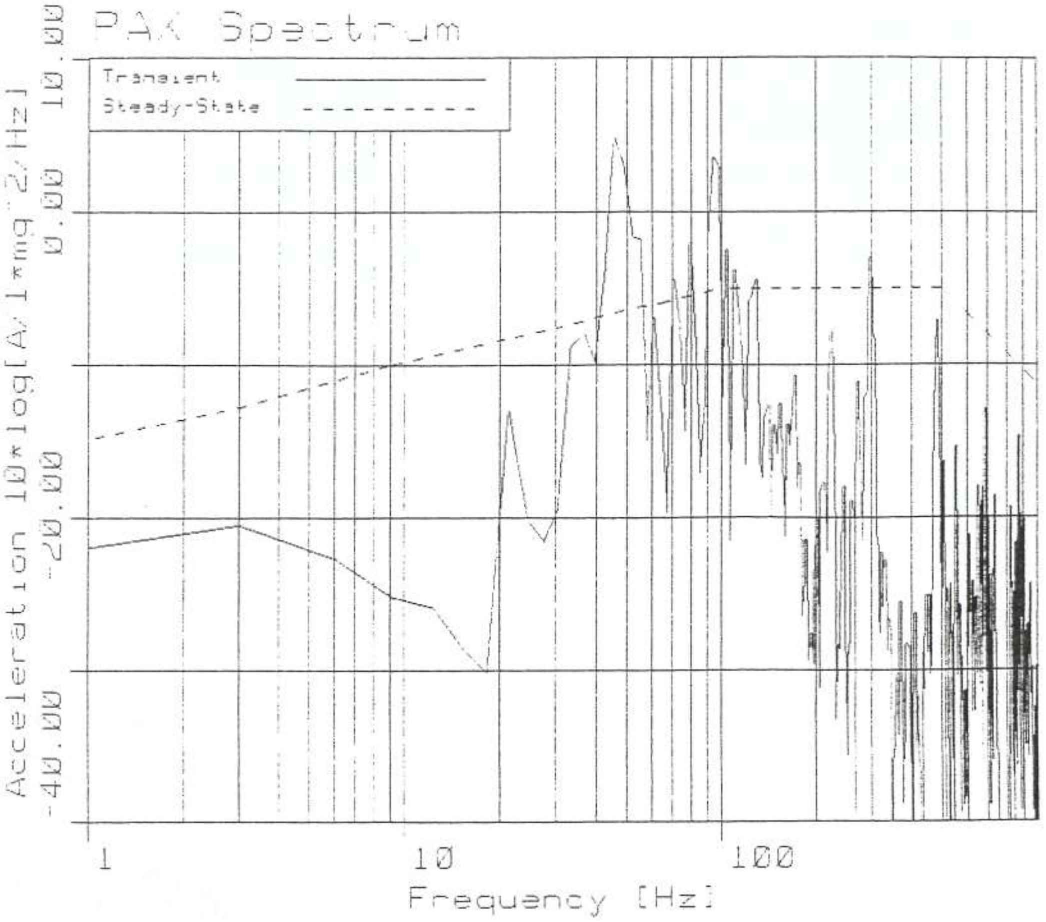
acquisition period at [illegible] < 5m.

data transmit path
data receive path
tracking signal path
acquisition signal path
beacon signal path

(moving part) : 65 kg



SILEX TERMINAL OVERALL BLOCK DIAGRAM



SPECTRUM OF MICROVIBRATIONS AT SPACECRAFT /

TERMINAL INTERFACE

SILEX

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user [illegible]
2Mbps [illegible]

COMMUNICATION CHARACTERISTICS

DATA RATE	50 MBPS
MODULATION SCHEME	DIRECT INTENSITY MODULATION 4PPM
BER	10^{-6}
BURST ERROR RATE	10^{-6}

TRANSMITTER CHARACTERISTICS

WAVELENGTH	830 NM
OPTICAL POWER	100 MW PEAK
TELESCOPE DIAMETER	25 CM
MAXIMUM POINTING ERROR	1.7 MICRORAD

LD: SDL: USA
SDC: UK
300mW [illegible]
[illegible] Life Test [illegible]
5000 hrs.

RECEIVER CHARACTERISTICS

DATA DETECTOR	AVALANCHE PHOTO DIODE
NOMINAL OPTICAL POWER	-56 DBM AT 65 MBPS BER 10^{-6}

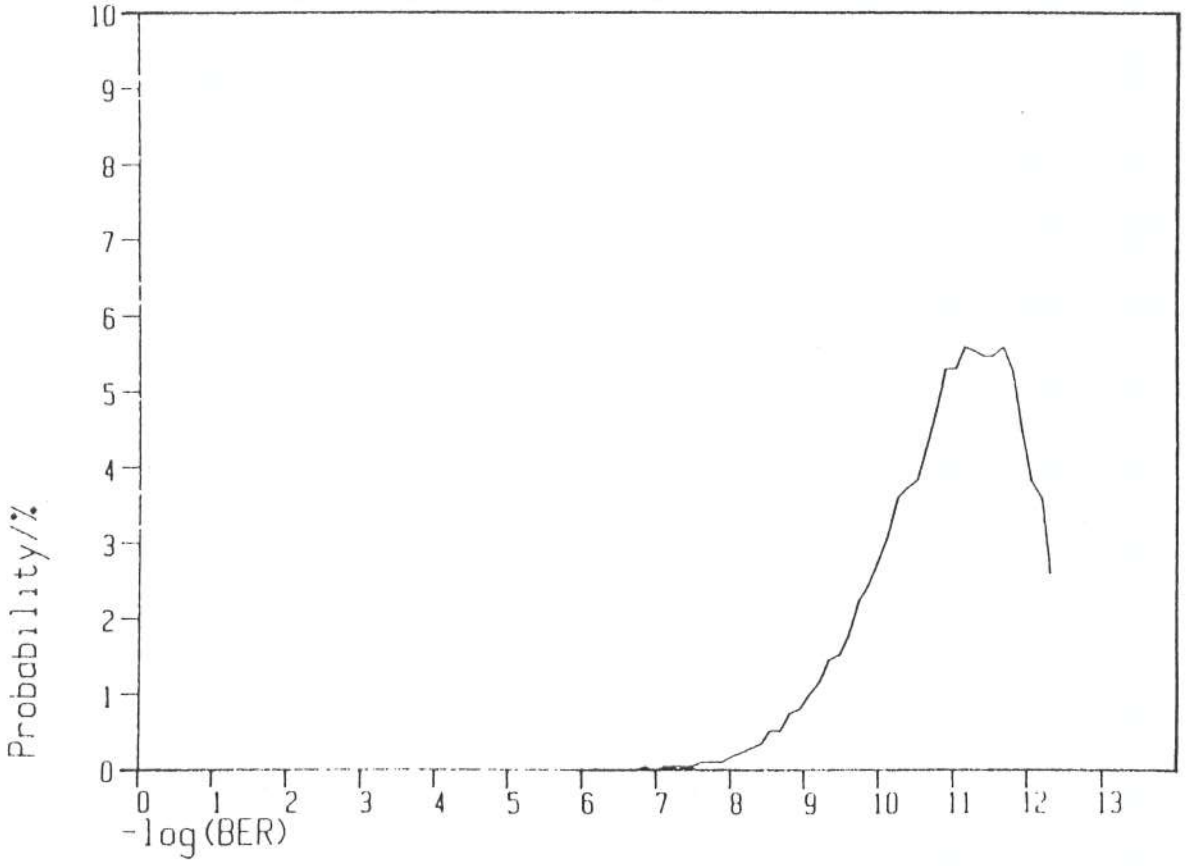
TERMINAL OVERALL MASS

110 KG

TERMINAL POWER DEMAND

140 W IN NOMINAL COMMUNICATION MODE

Beacon Diode
500mW LD array
SDL
SDL.
Test中



SILEX: Histogramme of Bit Error Rate for the optical space to space link

10^{-6}. ms. BER悪く[illegible].

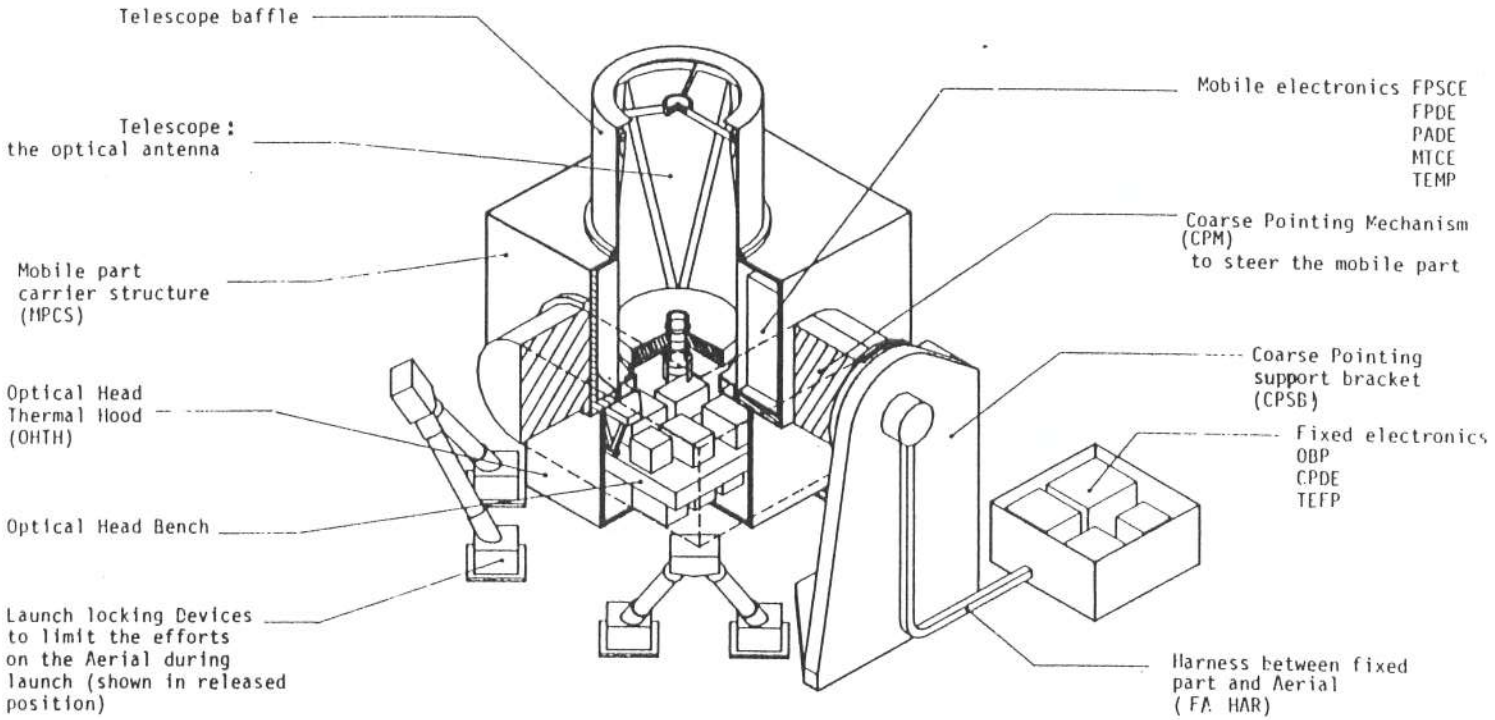
10^{-8}: not negligible

SILEX

esa

		DATA TRANSMISSION		TRACKING GEO		ACQUISITION GEO -> LEO		ACQUISITION LEO -> GEO	
			dB(m)		dB(m)		dB(m)		dB(m)
WAVELENGTH	nm	830		830		810		830	
TRANSMITTER POWER	mW	30	14.8	30	14.8	2500	34dBm	30	14.8
ANTENNA DIAMETER	cm	25		25		25		25	
G			119.6		119.6		80.7		119.6
LOSSES			-4.3		-4.3		-4.3		-4.3
TRANSMITTER TRANSMISSION			-2.2		-2.2		0		-22
EIRP			127.9		127.9		110.4		127.9
POINTING LOSS		0.42	-1.9	0.42	-1.9		0		-3
MEAN	µrad	0.215		0.215					
RMS	µrad								
BURST ERROR RATE		10^{-6}		10^{-6}					
DISTANCE	km	45 000		45 00o		45000		45000	
SPACE LOSS			-296.7		-296.7		-297		-296.7
RECEIVER ANTENNA DIAMETER	cm	25		25		25		25	
G			119.6		119.6		119.8		119.6
LOSSES			-0.3		-0.3		-0.3		-0.3
RECEIVER TRANSMISSION			-3.4		-13.3		-12.6		-22.2
RECEIVED POWER			-54.8		-64.7		-79.7		-74.7
BACKGROUND POWER	pW	390	-65	1.6	-88				
BIT RATE	Mbit/s	65							
BER		10^{-6}							
REQUIRED RECEIVED POWER			-59		-70	>9	-80	4	-82
MARGIN			4.2		5.3		0.3		7.3

SILEX LINK BUDGET



Optical Head Enclosure : the highly stable core of the terminal which inbeds the optical and opto-electrical equipments.
It includes :
- the Optical Head Bench
- the Optical Head Thermal Hood
- the units : ASDU, TSDU, FPM, PAM
  Optical components and filters
  LDTP, optical relays

SILEX TERMINAL
PHYSICAL LAY-OUT

SILEX

esa

	GEO	LEO
MASS (kg) :		
Fixed part	23	20
Aerial	77	75
TOTAL MASS (without spacecraft adaptation)	100	95
POWER (Watts) during :		
ACQUISITION	170	130
COMMUNICATION	**135**	**125**
STAND BY	60	60
AERIAL VOLUME (mm^3) :	870 x 910 x 1130	770 x 1100 x 1100

MASS BUDGET OF THE SILEX TERMINALS

SILEX

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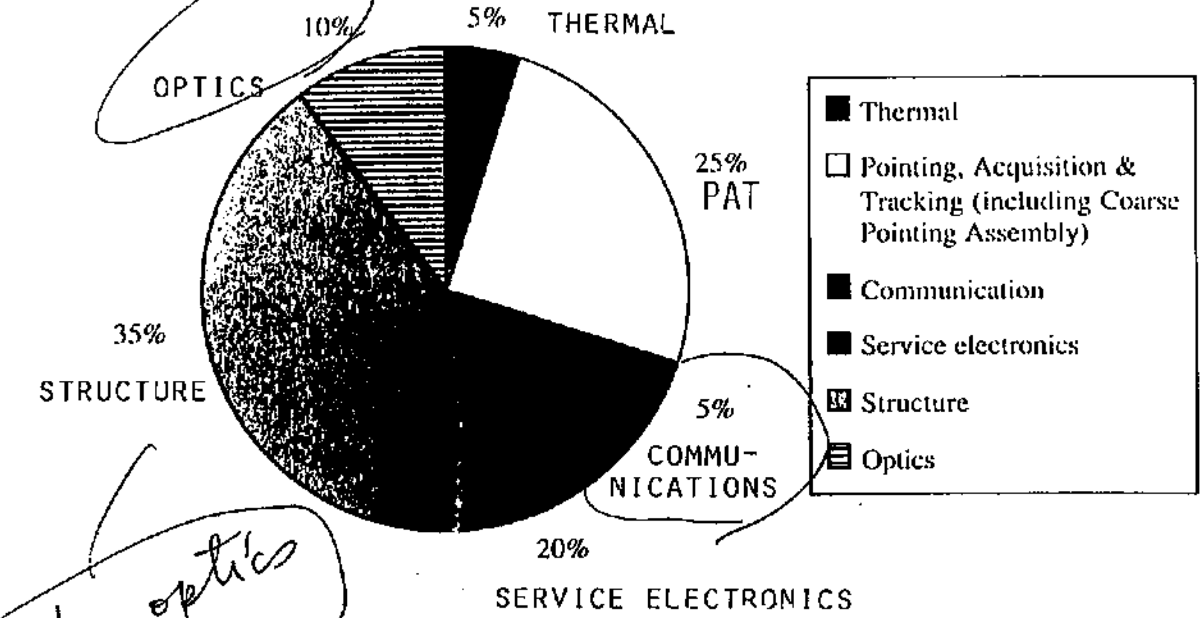
25cmφ telescope
8kg.



size
weight
cost

rf—system

φ/A

fiber optics を使っている.

MASS BUDGET OF THE SILEX TERMINALS

SILEX

esa

mission down from budget.

GEO to GEO Link deleted

forward data rate

return & modulation scheme.

65 — 02

65 — 050

4PPM → NRZ

Telescope ∅ 25cm∅ is max. (financial purposes).

	1991	1992	1993	1994
Start of Phase C/D	▲			
Thermal Model to SPOT	△			
Structural Model to SPOT		△		
LEO Terminal Mechanical/ Thermal Qualification Test		—		
Electrical Model to SPOT		△		
FM-LEO AIT		—	—	
FM-LEO to SPOT			△	
FM-GEO AIT			—	—
FM-GEO to ARTEMIS				

SILEX

MAIN EFFORT AREAS OF FUTURE ACTIVITIES

* HIGH POWER TRANSMITTERS :
  - ND:YAG TRANSMITTERS : POWER UP TO 1W
  - SEMICONDUCTOR LASERS: POWER 250 MW

* COHERENT RECEIVERS:
  - DATA RATE UP TO 600 MBIT/S
  - SENSITIVITY OF LESS THAN 100 PHOT./BIT

* POINTING, ACQUISITION AND TRACKING SYSTEMS
  - ADVANCED ACQUISITION STRATEGIES TO RELAX THE REQUIREMENTS OF THE MECHANISMS AND OF THE OPTICAL SYSTEM

* OPTICAL TECHNOLOGIES:
  - EFFICIENT COUPLING OF LASER BEAMS INTO FIBERS
  - FIBER-OPTIC WAVELENGT/POLARIZATION MULTIPLEXER
  - MICROOPTICS

1 W CW diode pumped Nd:YAG transmitter laser breadboard for coherent space communications

(developed by DORNIER, ADLAS, SIEMENS in Germany)

Configuration:

High power single mode oscillator, non-resonant amplifier

Oscillator:

Single end pumped twisted-mode linear discrete resonator pumped by two polarization coupled 1 W diodes

Amplifier:

Three stage end pumped double-pass rod amplifier each stage pumped by one 1 W diode

Measured performance:

output power (diodes operated at 900 mW)	1010 mW
wavelength	1064 nm
spectral quality	single mode
linewidth	< 20 kHz / 10 ms
frequency stability	< 600 kHz / min
spatial quality	diffraction limited TEM00
effective waist	226 um (h), 277 um (v)
beam wandering	< 10 % divergence
polarization	1 : TBD linear
electrical to optical conversion efficiency	6.3 %

岡田(東海大) pre-ampの実用化?

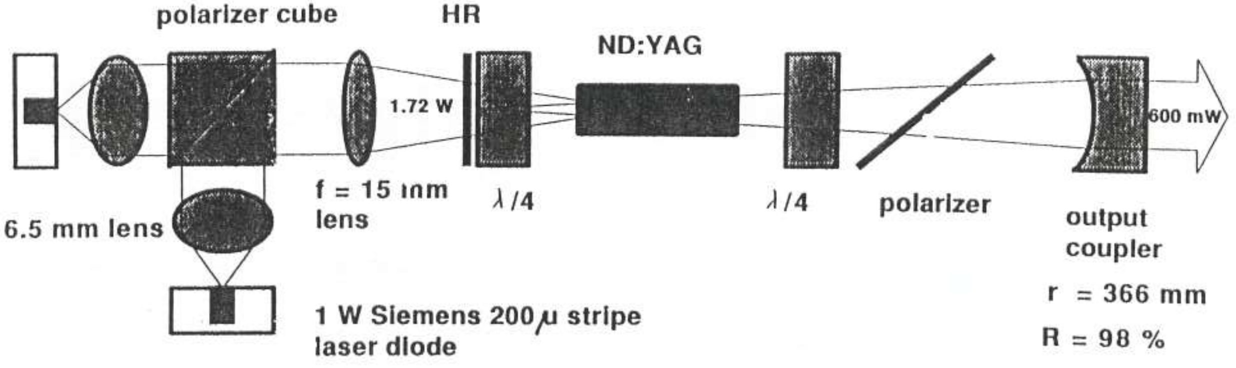
TX、 YAG等. 3段

Rx: high gain Rx. noise と amp 等. quantum noise spontaneous emission.

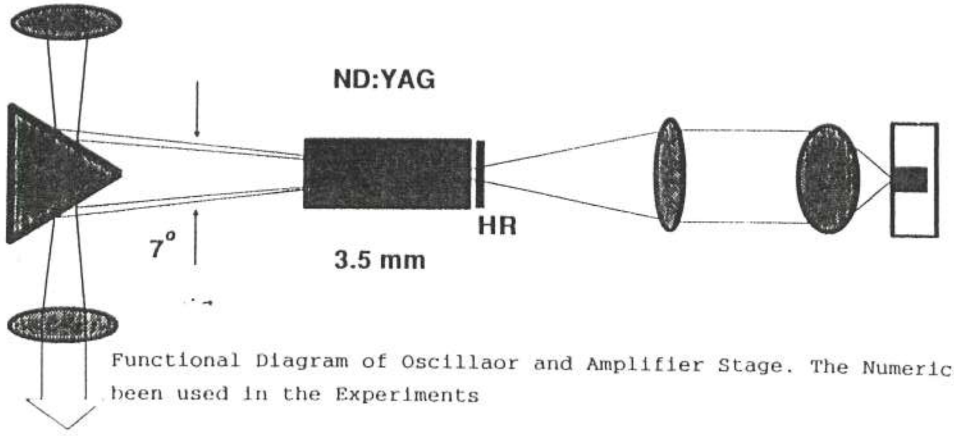
Laser amp は noise less

[illegible]: noisy & noisy.

End pumped twisted mode linear discrete resonator

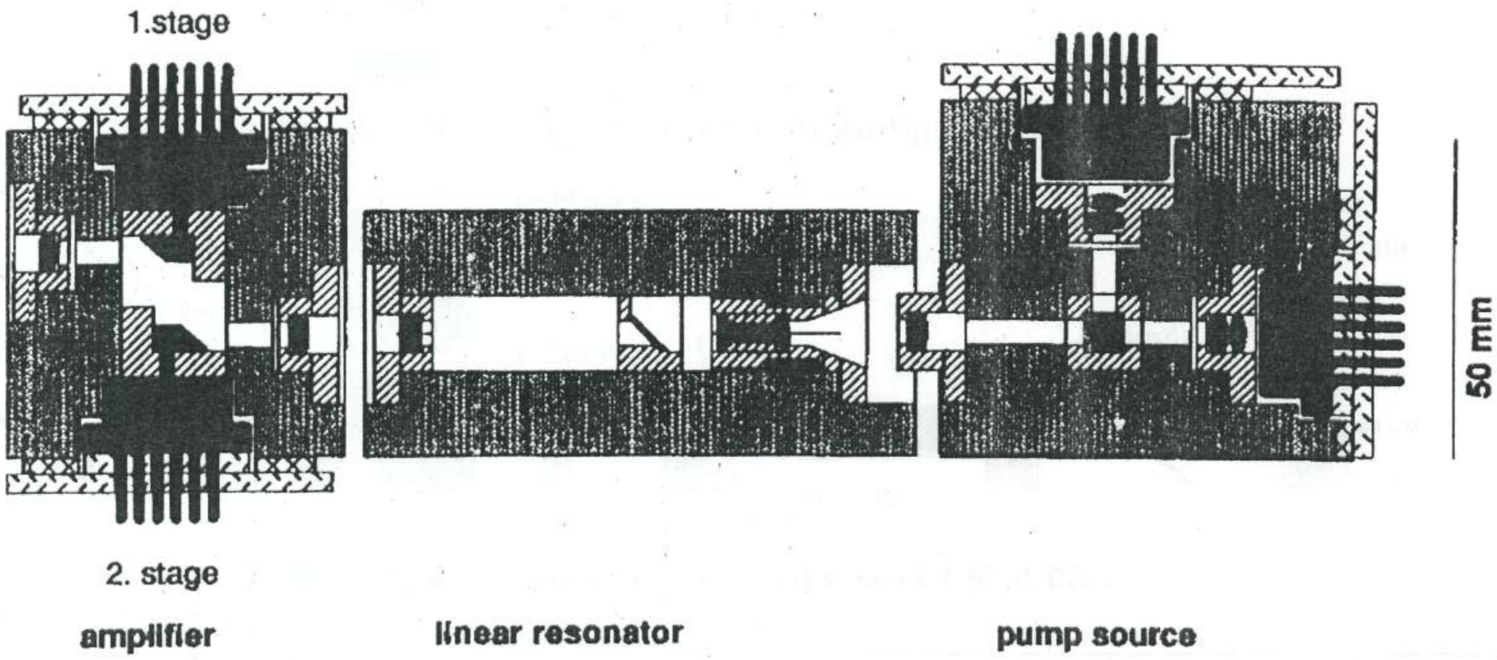


Two pass end pumped non resonant amplifier



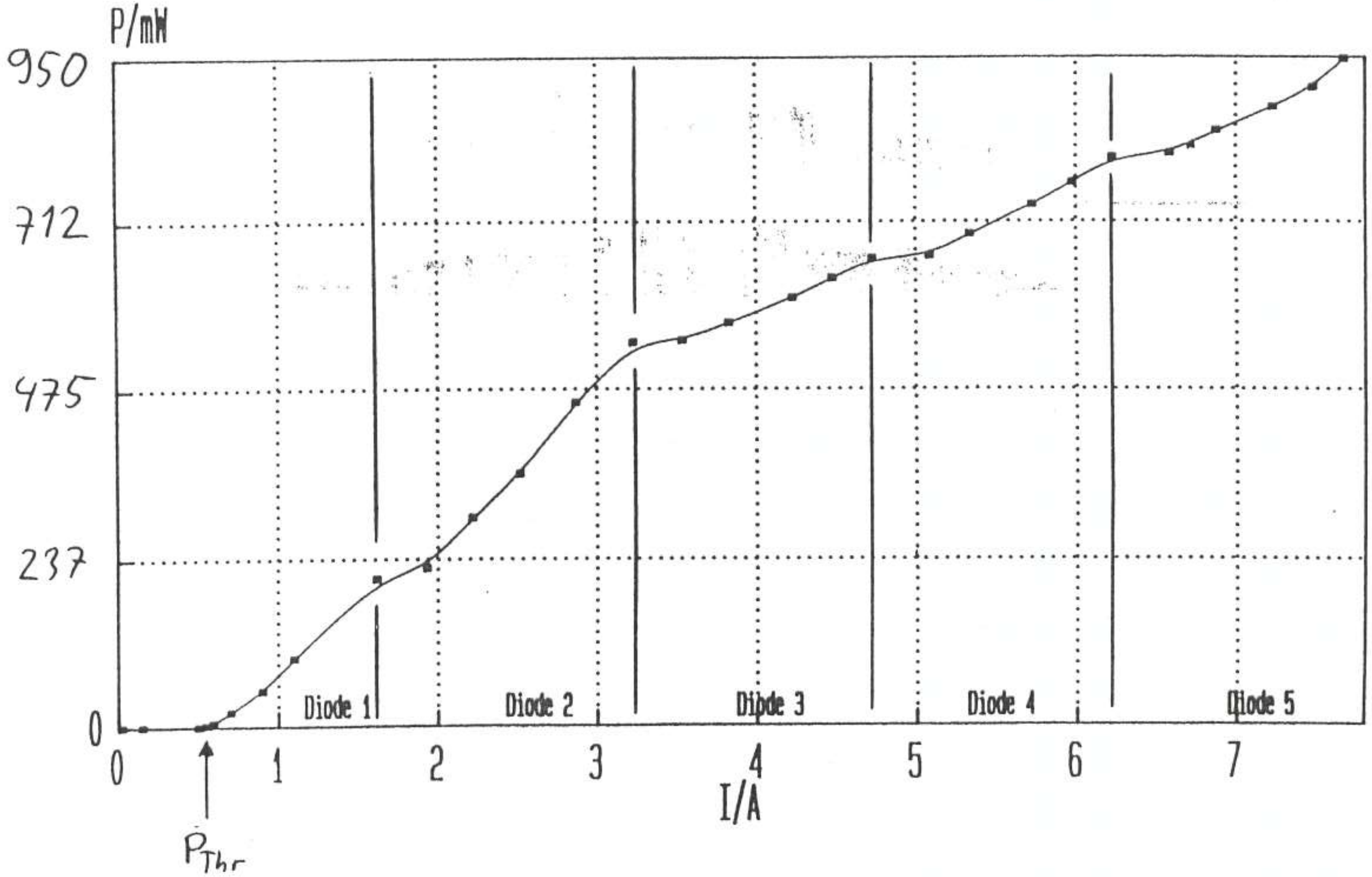
Functional Diagram of Oscillaor and Amplifier Stage. The Numerical Values have been used in the Experiments

SILEX



Conceptual space design (pump diodes not redundant)

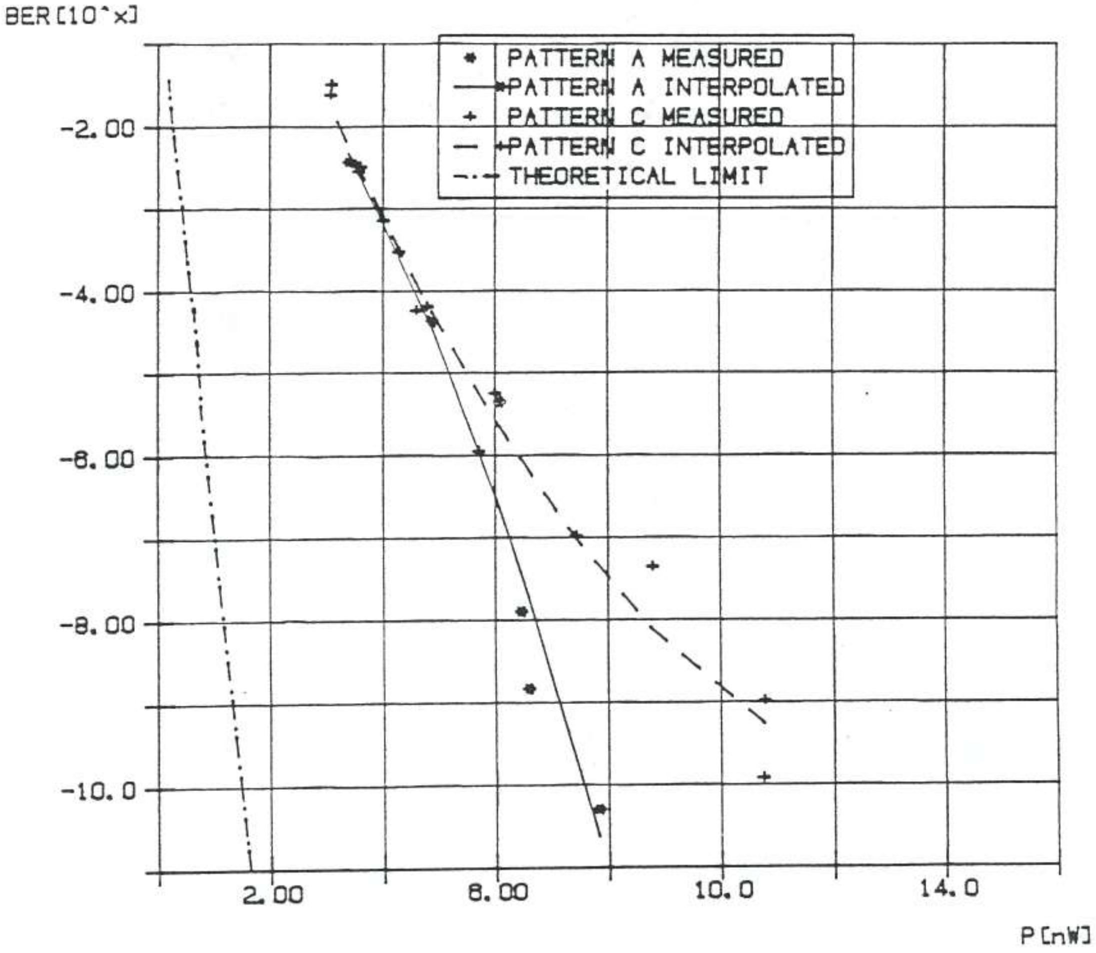
Single side pumped - Linear resonator - two stage amplifier Configuration



Laser Diodes Drive Current Versus Laser Output Power Characteristics (U_{NTC}(res) = 2.220 V)

MEASURED SENSITIVITY OF A ND:YAG ASK HETERODYNE RECEIVER

(DATA RATE = 140 MBIT/S)



Bit error rate as a function of receiver input signal power. Pattern "A" is a 1-01-0 sequence, Pattern "C" ist a 16 bit word with zero mean.

1-3

Recent developments in optical space communication technologies at ATR

Yoji Furuhama

**ATR Optical and Radio
Comms. Res. Labs.**

IWOSC '90

December 6 and 7, 1990, ATR, Kyoto

Recent Developments in Optical Space Communication Technologies at ATR

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Seika-cho, Soraku-gun, Kyoto 619-02, Japan
Telephone: +81-7749-5-1511
Fax: +81-7749-5-1508

Abstract

ATR Optical and Radio Communications Research Laboratories was established in April 1986 with support from the Japan Key Technology Center and 140 private companies. A commitment was made to continue this support for 10 years. One of our main research themes is basic research on optical intersatellite communications.

We began in 1986 with a survey of the status of optical space communication related technologies. We calculated the budget for an optical communication link, assuming certain specifications and components obtainable in the near future. From this we established the need for a laser diode with 400 mW of output power and a communication link capacity of 400 Mbit/s at a bit error rate (BER) of 10^{-9} in the case of an intensity modulation direct detection (IM/DD) scheme. We have designed and constructed an IM/DD modem with off-the-shelf components and have measured the characteristics of BER performance versus received optical signal power.

The quality of an optical space communication link degrades due to natural background noise. An Etalon optical filter has been considered in order to maintain communication link quality under background noise in a direct detection scheme. An Etalon filter whose free space ranges fits the londitudinal mode interval of the laser diode has been proposed, and its applicability to optical space communications has also been shown.

Beam tracking schemes robust to background noise are also discussed. Here we have proposed an optical beam tracking method whose tracking signals are extracted from the received communication signal without the use of either beacon signal or an additional tracking signal.

We assume two randomly vibrating satellites with gaussian statistics which are facing each other. An increase in the pointing error of one satellite causes a decrease in the received power at the other satellite and an increase in the beam arrival angle estimation error. Under these considerations we have derived the system parameters required for stable bidirectional tracking/pointing operations.

A free-space simulator for a laser transmission experiment has been proposed. The simulator allows the following: (1) evaluation with respect to optical beam forming and control, (2) evaluation of system characteristics in acquisition, tracking, and pointing, (3) dynamic simulation of a dual-direction optical ISL. Further information will be given in another IWOSC '90 presentation.

Author's Biography

YOJI FURUHAMA was born in Kure, Japan on March 1, 1940. He received the B. S., M. S., and Dr. Eng. degrees in electronics engineering from Kyoto University, Kyoto, Japan in 1963, 1965, and 1971, respectively.

From 1968 to 1986 he was with the Radio Research Laboratory, Ministry of Posts and Telecommunications, Tokyo. During 1974-1975, he was a guest scientist at WPL/ERL/NOAA, Colorado. He joined Advanced Telecommunications Research Institute International in 1986. He is now a Director of the Optical and Radio Sciences Research Division of ATR International and also the President of ATR Optical and Radio Communications Research Laboratories.

He is the author of numerous papers in the field of microwave propagation in rain filled media, millimeter wave utilization, and microwave remote sensing, and is a co-author of a book on microwave remote sensing from satellites. He was awarded the Maejima Prize by the Communications Association of Japan in 1985.

His current interests include basic research relating to light- and radio-wave communications and microwave remote sensing of man's geophysical environment.

Dr. Furuhama is a member of the Institute of Electronics, Information and Communications Engineers, the Remote Sensing Society of Japan, and the Institute of Electrical and Electronics Engineers.

Recent Developments in Optical Space Communication Technologies at ATR

Yoji Furuhama
ATR Optical and Radio Communications Research Laboratories

December 6, 1990

International Workshop on Optical Space Communication

Agenda

CONTENTS

1. Introduction
2. Link Budget and IM/DD
3. Etalon Optical Filter
4. Beam Tracking Schemes Robust to Background Noise
5. Pointing / Tracking Interaction between Two Satellites
6. Free-space Simulator for Laser Transmission
7. Conclusion

References

Optical ISL Research Projects

ATR

0 1986 87 2 88 89 4 90 91 6 92 93 8 94 95 10 → SSF-JEM

ETS-VI

Fundamental Studies | **System Evaluations** | **System Integrations**

Optical Beam Control

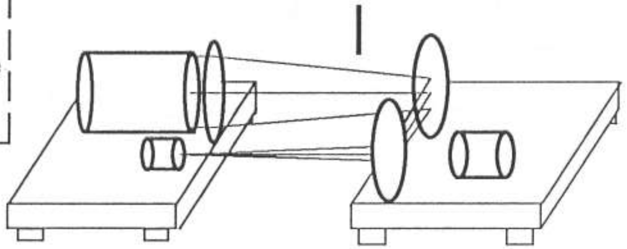
Interaction between Two Satellites

Compact Optical Transceiver

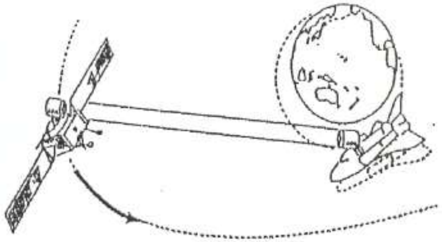
Free-space Simulator for Laser Transmission

Dual-direction Link Simulation

Realization of Precise Beam Control / Measuring Technique (Finer than Micro-radian)



- **Establishment of Experimental Subsystem to Indicate Technical Feasibility**
- **A Candidate for SSF-JEM Experiments**



Optical Modulation

IM / DD

Coherent

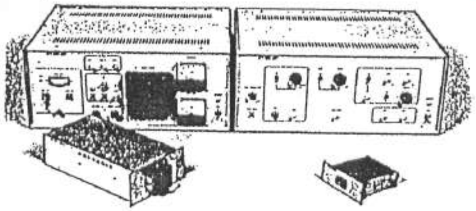
Link Budget Calculations

High-power / High Bit-rate MODEM

Spacial Matching / Optical Frequency Tracking

System Evaluations

IM / DD	• **Realization of High-power Transmission** • **Countermeasure for Solar Background Noise**
Coherent	• **Compensation of Frequency, Doppler Shift and Beam Tracking Error**



Related Topics

- **Development of Optical Device such as High-power LD and Fine-resolution CCD**
- **Development of On-board Model**
- **Field Experiment in Space**

Introdunction

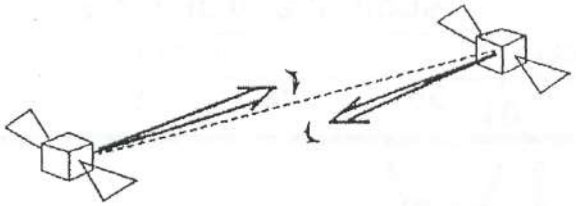
Research on Optical Intersatellite Communication System

Superiority of Intersatellite Communication System

- Efficient Use of Frequency and Geostationary Orbit Resources
- Enhancement of Flexible Inter-connectivity in Satellite Communication Networks
- Infrastructure Supporting Future Activities in Space

Superiority of Applying Optical Technologies

- Large Transmission Capacity with Compact and Light-weight Equipment
- Sharp Beam Divergence / Absence of Inter-system Interference, Low Energy Consumption



Introdunction

Research Program on Optical ISL in ATR

Technical Interests:

- **Optical Modulation Technologies**

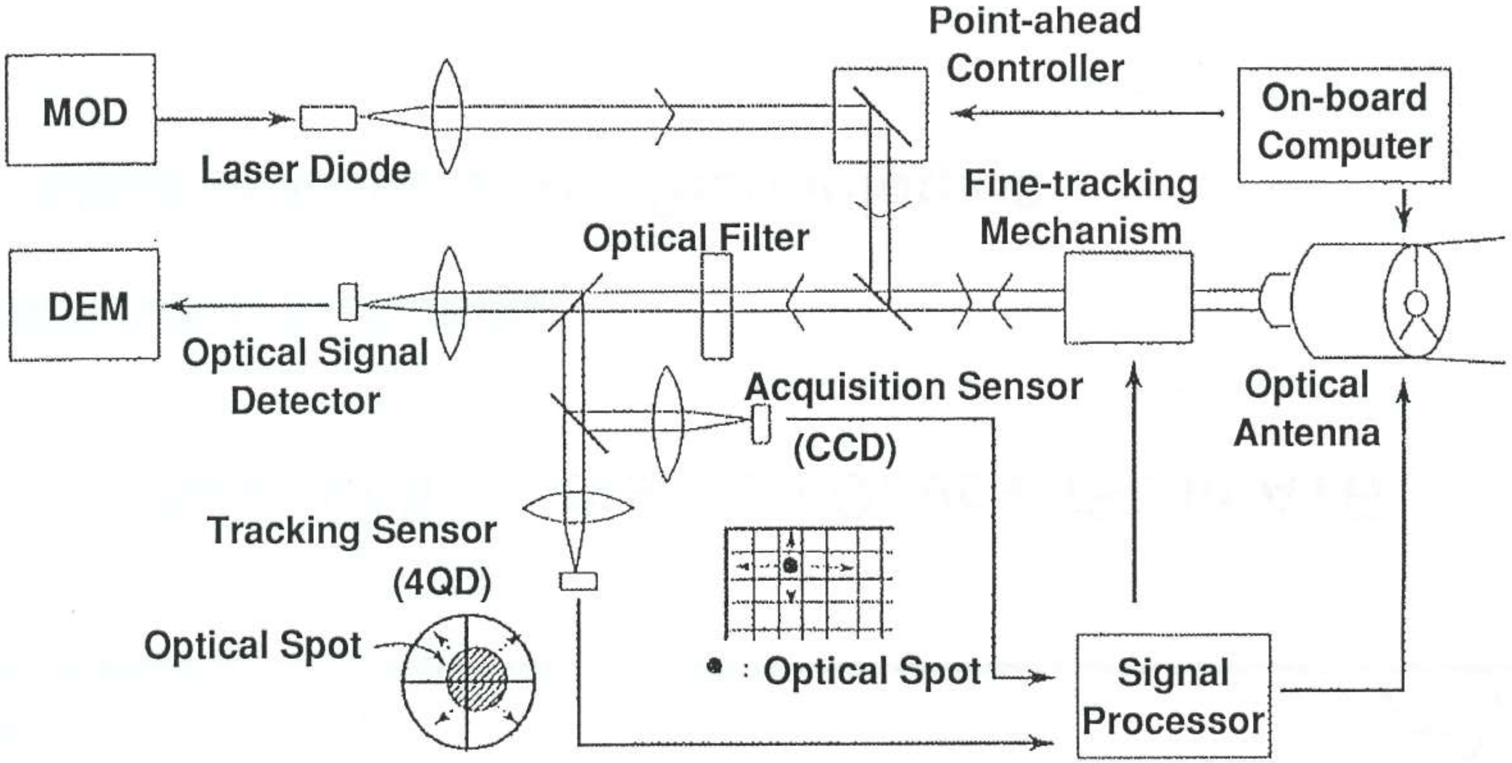
  (IM/DD, Coherent)

- **Optical Beam Control Technologies**

  (Acquisition / Tracking / Pointing; GEO-GEO, GEO-LEO)

- **Optical Devices, Other Related Matters**

Optical ISL Communication Equipment

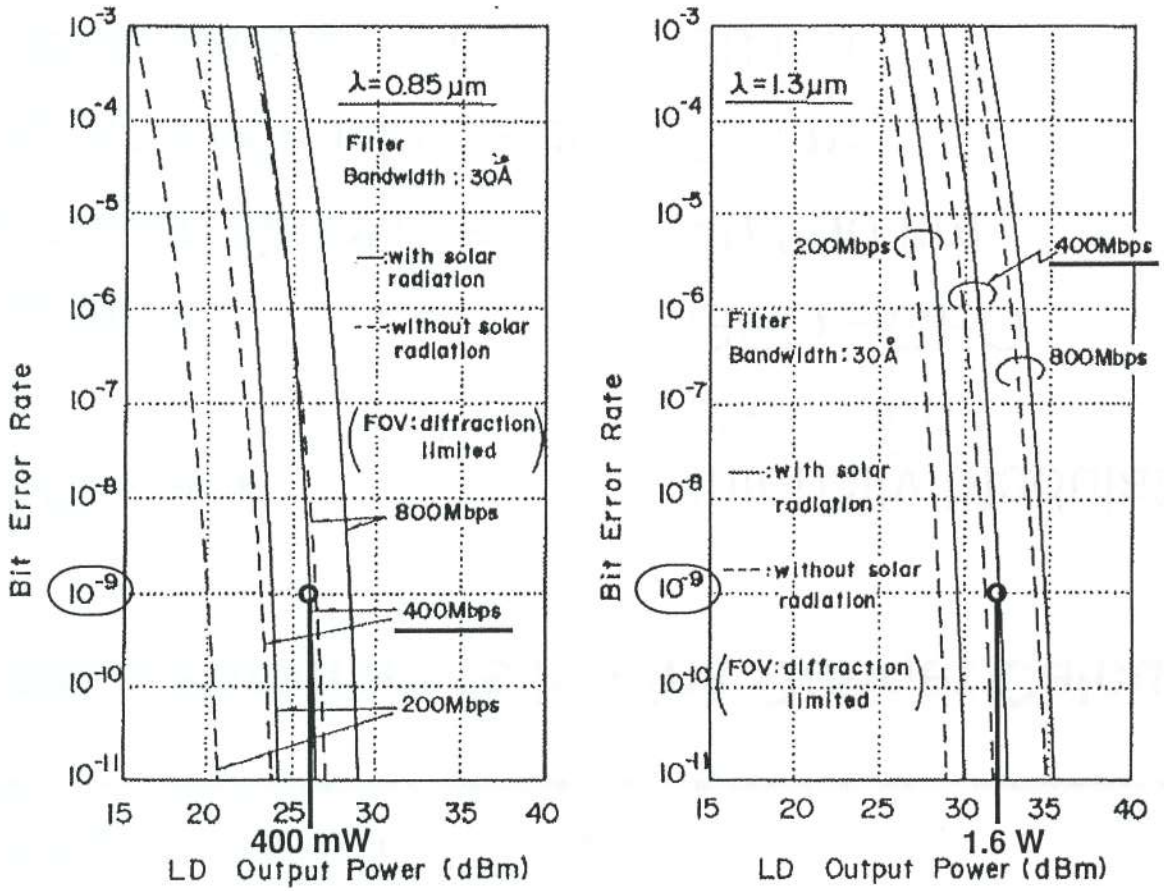


Assumed Parameters in Link Budget Calculation

Modulation Scheme : Intensity Modulation / Direct Detection
Link Configuration : GEO - GEO
Distance between Satellites : 40,000 km
Transmitting Antenna Diameter : 20 cm
Receiving Antenna Diameter : 20 cm
Solar Radiation : 7000 K
Optical Filter Bandwidth : 30 Å
Field of View of Receiver : Diffraction Limited

Link Budget and IM/DD

Bit Error Rate versus LD Output Power



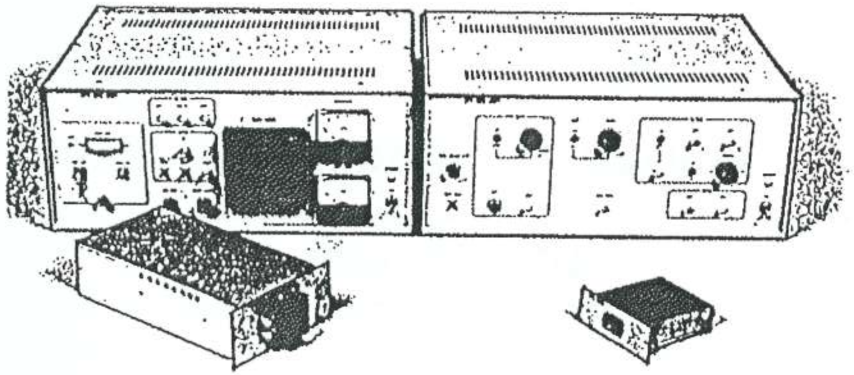
Link Budget and IM/DD

Major Performance Specifications

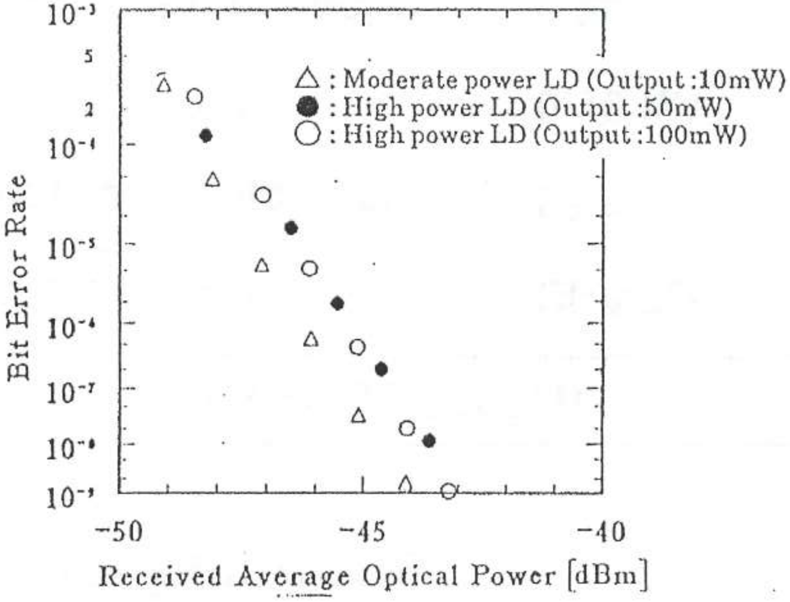
Modulator		Demodulator	
Average Light Output	: 100 mW	Photo Detector	: Si-APD
Wavelength	: ~ 800 nm	Quantum Efficiency	: 83 %
Transmission Bit Rate	: 360 Mbit/s	Dark Current	: 0.16 nA
Max. Bias Current	: 150 mA	Excess Noise Factor	: 0.25
Max. Signal Current	: 350 mA(p-p)	Equivalent Input Noise Current of	
Modulating Code	: NRZ	Pre-amplifier	: 4 pA/Hz$^{1/2}$
Temperature		Bandwidth	: 200 MHz
Control Range	: 10 ~ 30 °C		

Development of an IM/DD MODEM

Transmission Rate : 360 Mbit/s / LD Output Power : 100 mW



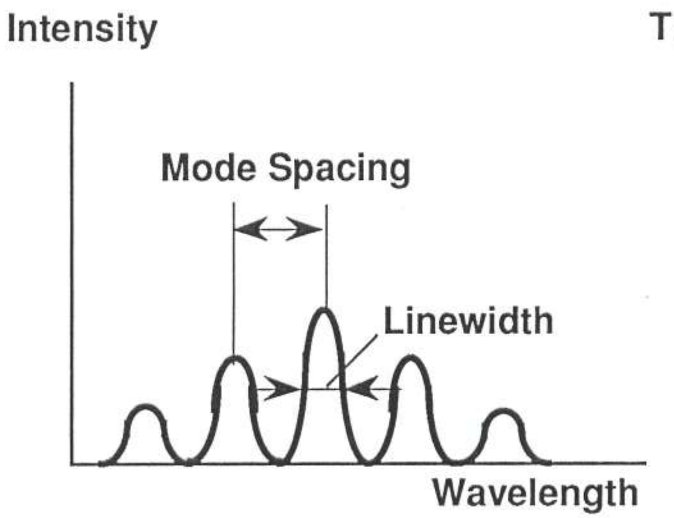
External Overview of the
Developed IM/DD MODEM



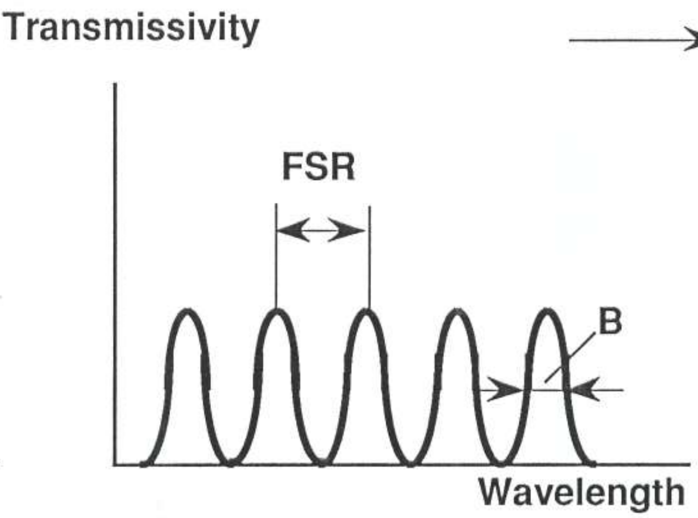
BER Performance vs. Received
Optical Signal Power

葉 coincide は偶然の一致を意味する。

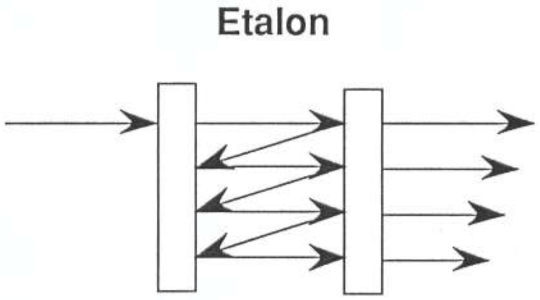
Similar Periodicity between LD Spectrum and Etalon Transmissivity



Spectrum of LD Oscillating in Multi-longitudinal Mode



Transmissivity of Etalon



FSR : Free Spectral Range

B : Bandwidth

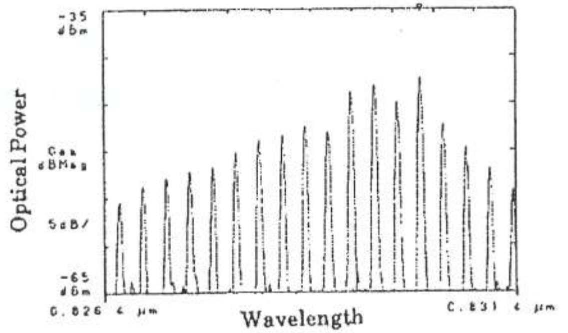
Finess = FSR / B

Etalon Optical Filter

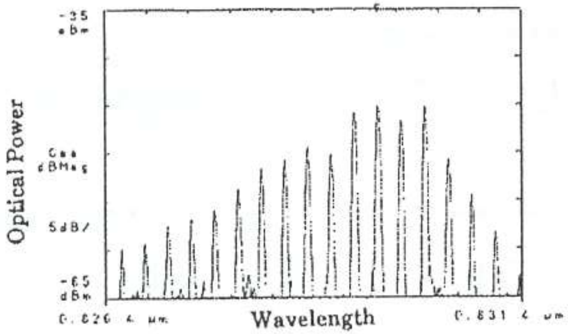
Examples of Etalon Transmissivity Characteristics

Multi-longitudinal Mode LD

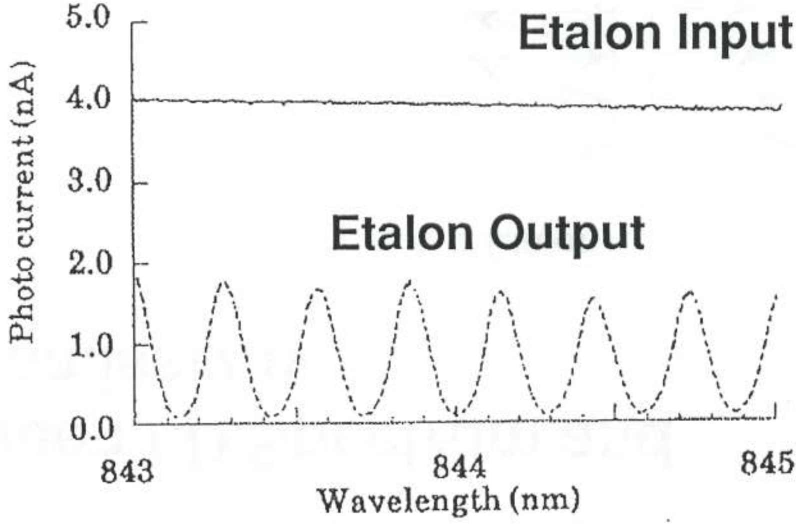
Etalon Input



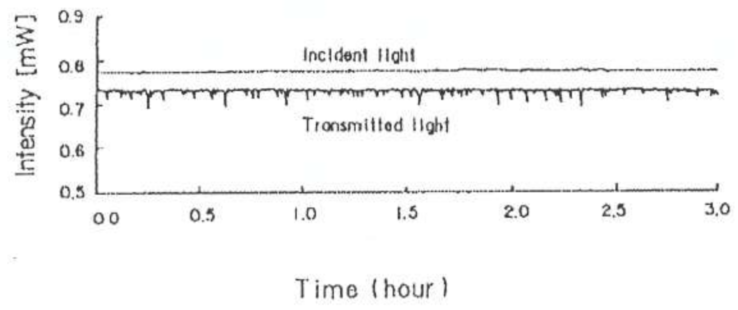
Etalon Output



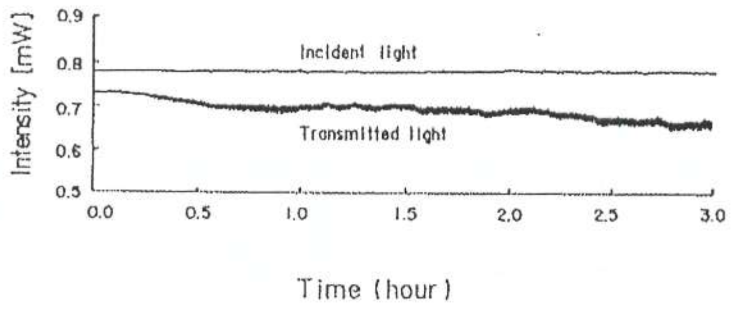
Xenon Lamp



Temporal Variation of the Throughput of Etalon Optical Filter



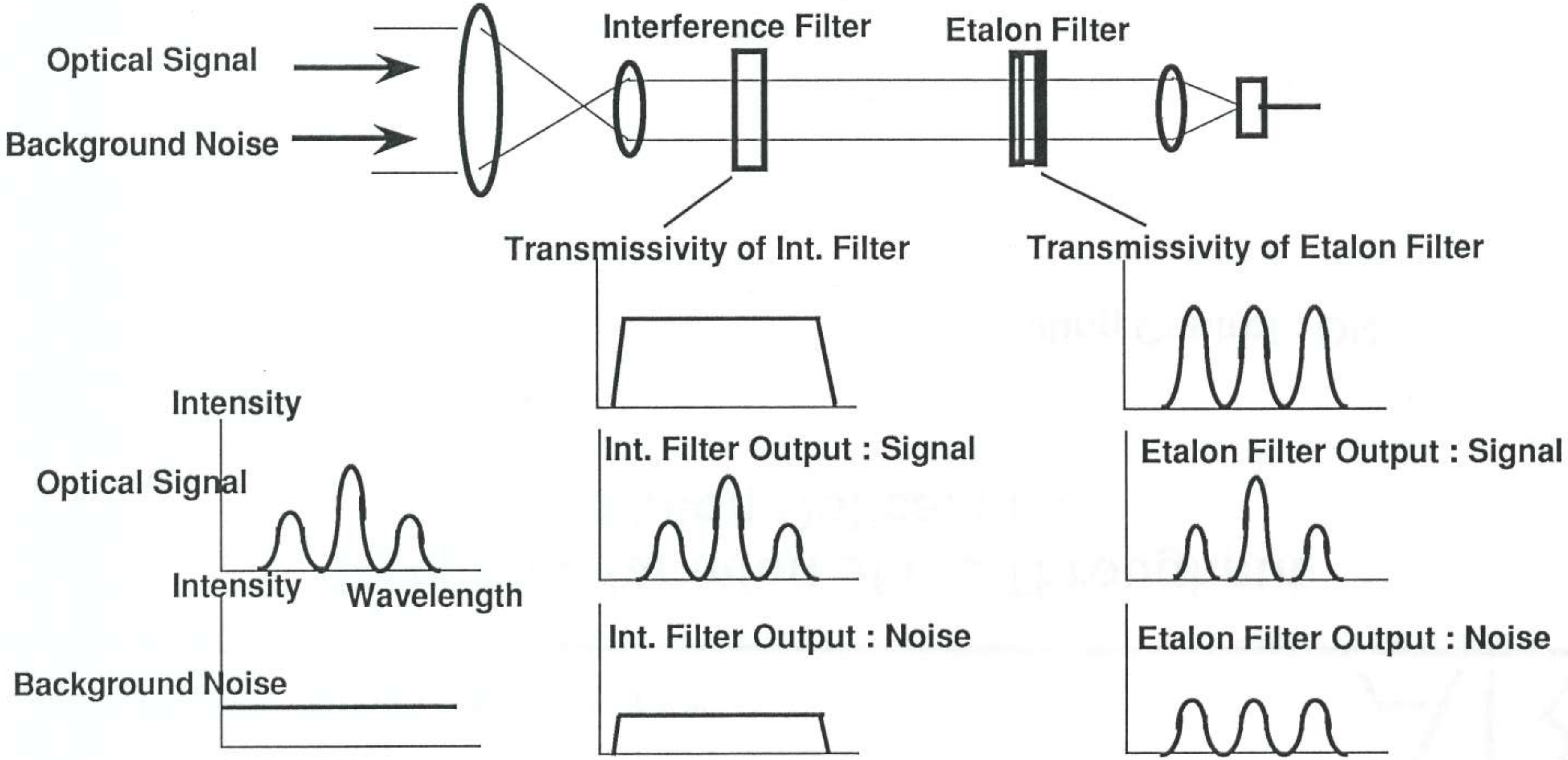
Tilting Control : ON



Tilting Control : OFF

Etalon Optical Filter

Etalon Optical Filter to Eliminate Background Noise



Optical Signal

Background Noise

Interference Filter

Etalon Filter

Transmissivity of Int. Filter

Transmissivity of Etalon Filter

Intensity

Optical Signal

Intensity

Wavelength

Background Noise

Int. Filter Output : Signal

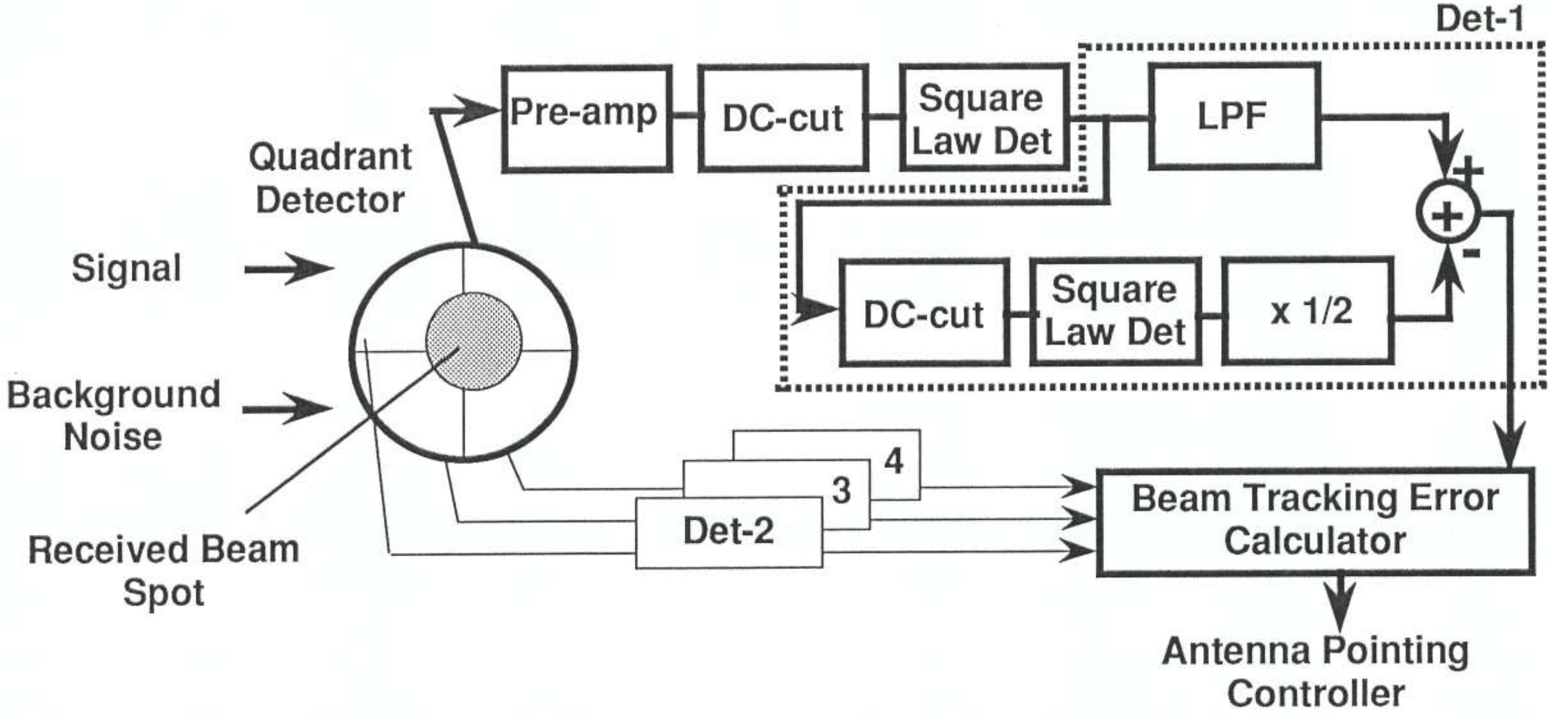
Int. Filter Output : Noise

Etalon Filter Output : Signal

Etalon Filter Output : Noise

Beam Tracking Robust to BG Noise

QD-based Beam Tracking Using AC Signal



Beam Tracking Robust to BG Noise

Auto-correlation of Square Law Detector Output

DC Noise = 1/2 AC Noise -> to be <u>Cancelled Out</u> !

$$Rz(\tau) = E[(s_1+n_1)^2(s_2+n_2)^2]$$

$$= E[s_1^2 s_2^2] + \quad 2E[s_1^2 n_1^2] + 4E[s_1 s_2 n_1 n_2] + E^2[n_1^2] + 2E^2[n_1 n_2]$$

Signal Component

DC Noise AC Noise DC Noise AC Noise

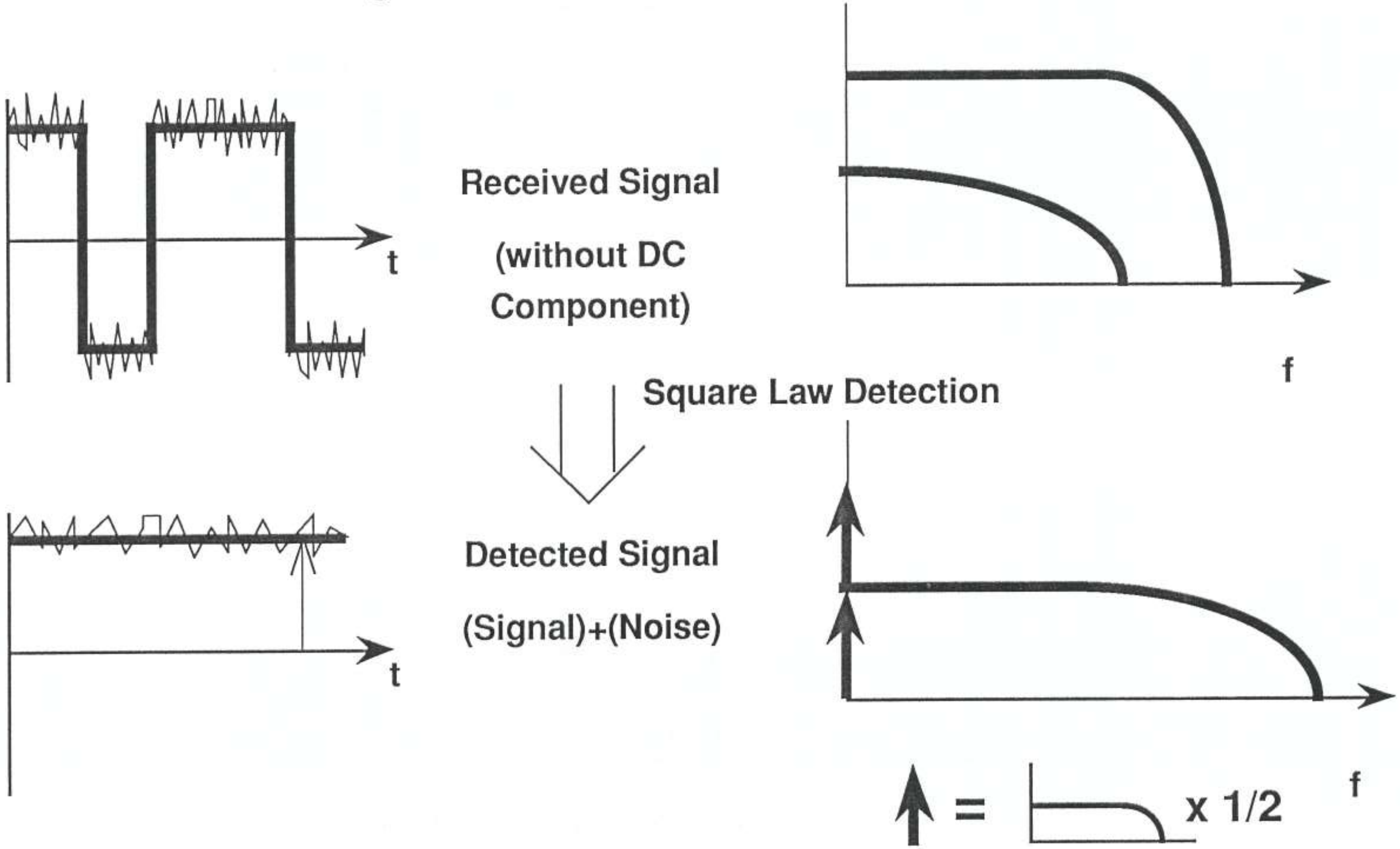
Noise Components

DC/AC Noise Power Ratio: 1 : 2 1 : 2

DC/AC Noise Power Ratio: 1 : 2

Beam Tracking Robust to BG Noise

Extract Signal Power as DC Component



Received Signal

(without DC Component)

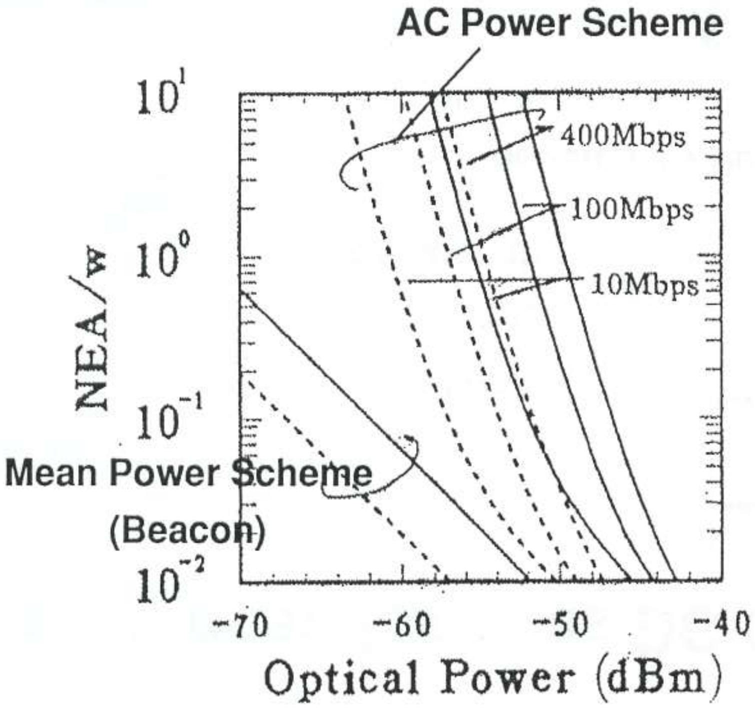
Square Law Detection

Detected Signal

(Signal)+(Noise)

Beam Tracking Robust to BG Noise

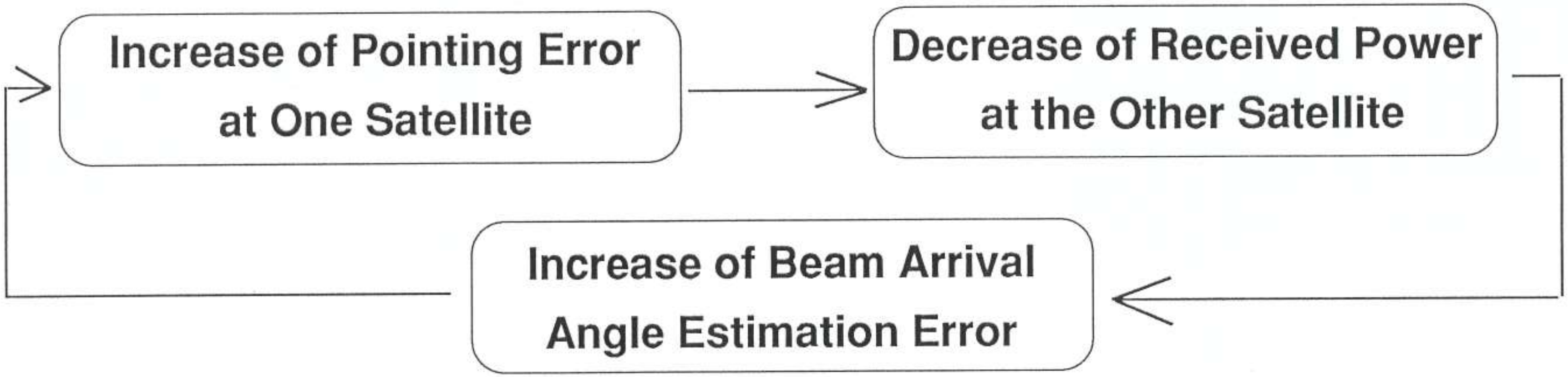
NEA / ω vs. Input Power



Dotted Line : With no BG Noise
Normal Line : With Sun Interference

Pointing/Tracking Interaction

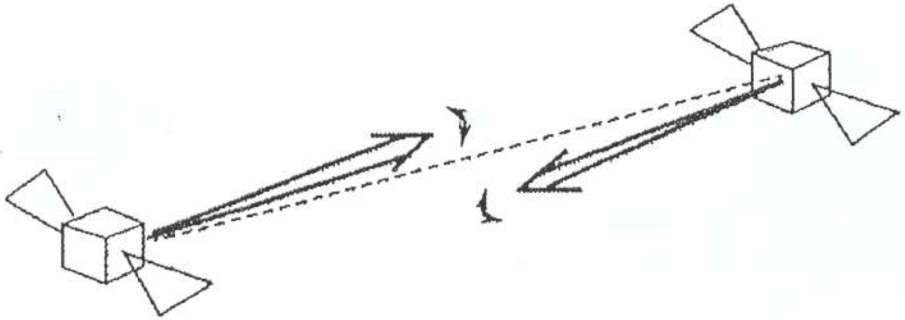
Interaction Flow between Two Satellites



Increase of Pointing Error at One Satellite

Decrease of Received Power at the Other Satellite

Increase of Beam Arrival Angle Estimation Error



Pointing/Tracking Interaction

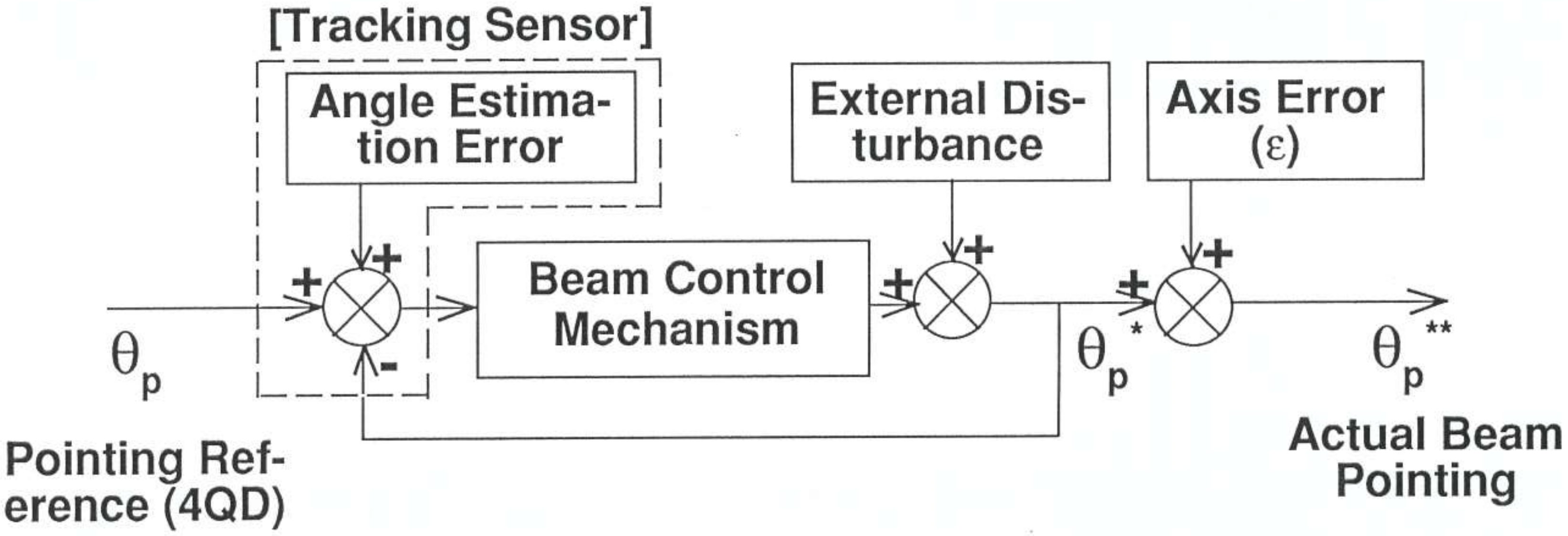
Assumptions for Analytical Investigation

(a) Attitute Fluctuations of Both Satellites
  - Gaussian Statistics

(b) Beam Pattern
  - Gaussian
  - Beam Divergence >> Sensor NEA and Axis Error

(c) Tracking Sensor Error
  Thermal Noise >> Shot Noise

Block Diagram of Tracking/Pointing Control System



[Tracking Sensor]

Angle Estimation Error

External Disturbance

Axis Error (ε)

Beam Control Mechanism

θ_p

Pointing Reference (4QD)

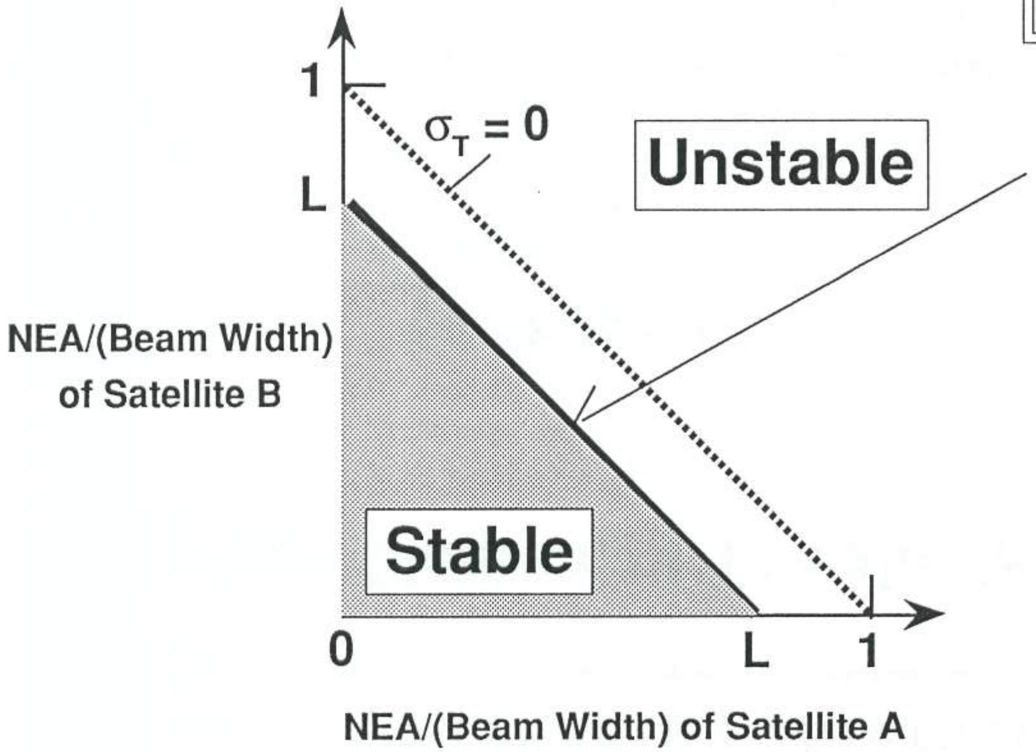
θ_p^*

θ_p^{**}

Actual Beam Pointing

Parameters for Stable Tracking/Pointing Operation

No Axis Error Condition



L: Determined by $\dfrac{\text{Residual Tracking Error}}{\text{Beam Width}}$

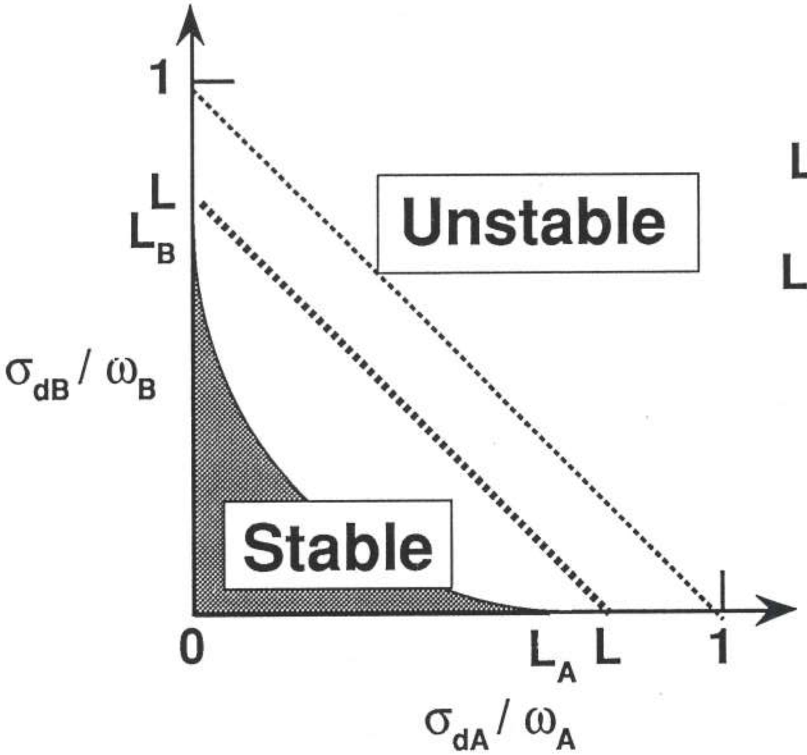
$$L = [(1 - \sigma_{TA}{}^2 / \omega_A{}^2)(1 - \sigma_{TB}{}^2 / \omega_B{}^2)]^{1/2}$$

σ_{TA}, σ_{TB} : Residual Tracking Error

ω_A, ω_B : $e^{-1/4}$ Beamwidth

Parameters for Stable Tracking/Pointing Operation

Including Axis Error



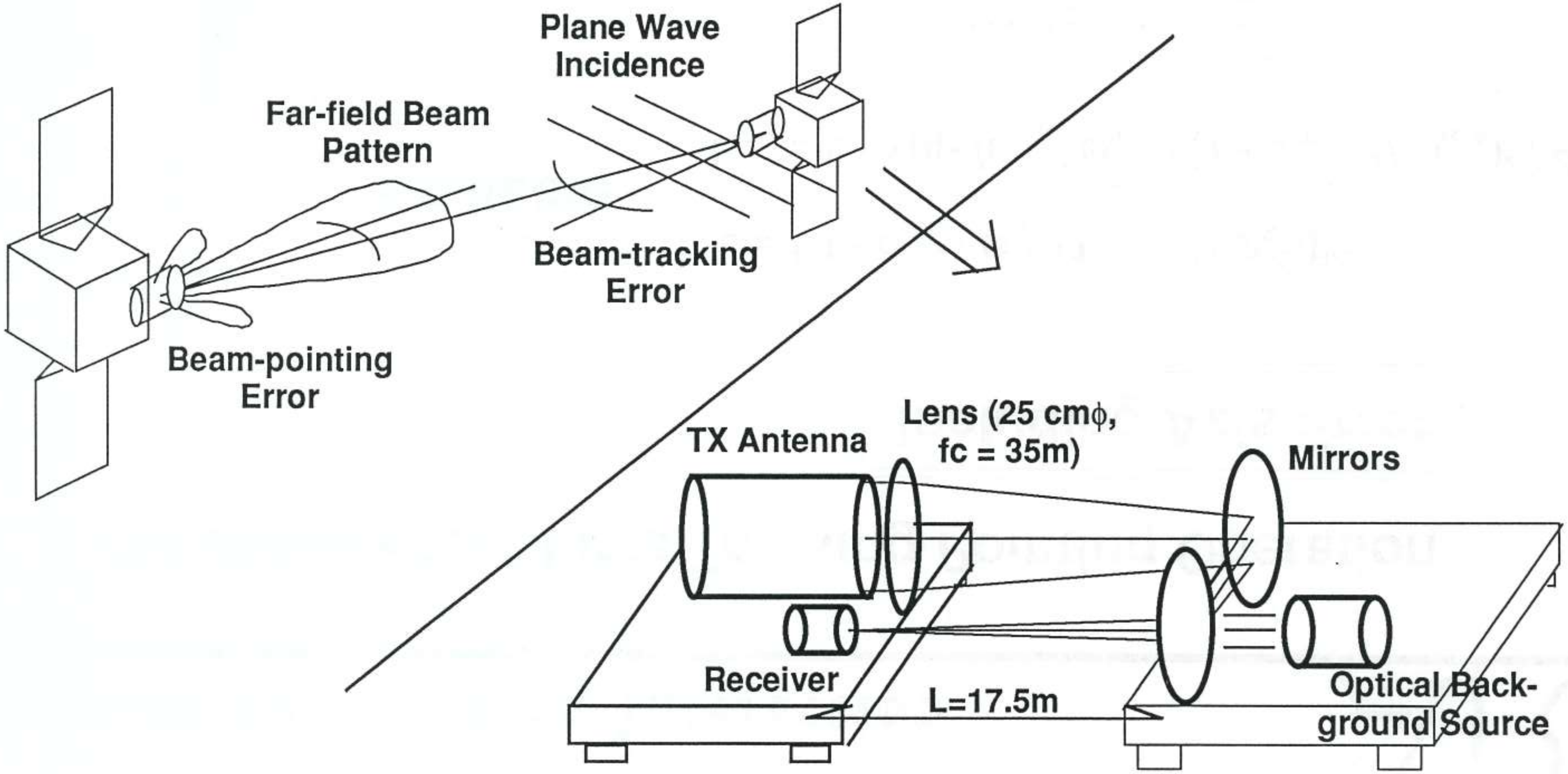
$$L = [(1 - \sigma_{TA}{}^2 / \omega_A{}^2)(1 - \sigma_{TB}{}^2 / \omega_B{}^2)]^{1/2}$$

$$L_{A,B} = L \exp[- (\varepsilon_{B,A} / \omega_{B,A})^2 (1 - \sigma_{TB,TA}{}^2 / \omega_{B,A})^2 / 4]$$

σ_T : Residual Tracking Error
ω : $e^{-1/4}$ Beamwidth
ε : Axis Error
σ_δ : Angle Estimation Error

Free-space Simulator for Laser Transmission

- Concepts -



Free-space Simulator

Optical Beam Specifications and Required System Parameters

-	Optical Beamwidth	~ 4 μrad (FWHM)*
-	Required Pointing Stability	< 0.3 μrad (rms)
-	Tracking Anglar Range	± 8 mrad (max)**
-	Uncertainty Cone Angle	3.5 ~ 8 mrad (max)**
-	Point-ahead Angle	0 ~ 70 μrad

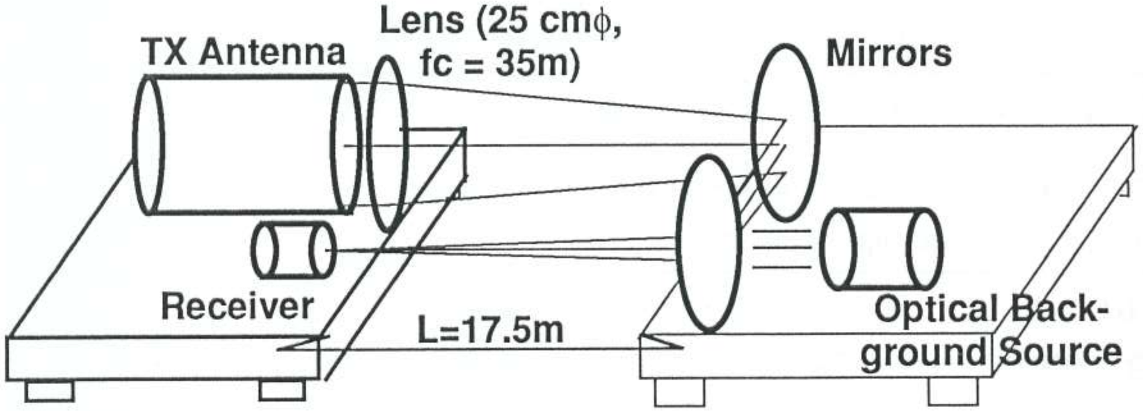
* assuming 20 cm antenna diameter and 0.8 μm wavelength

** residual of open-loop satellite position tracking

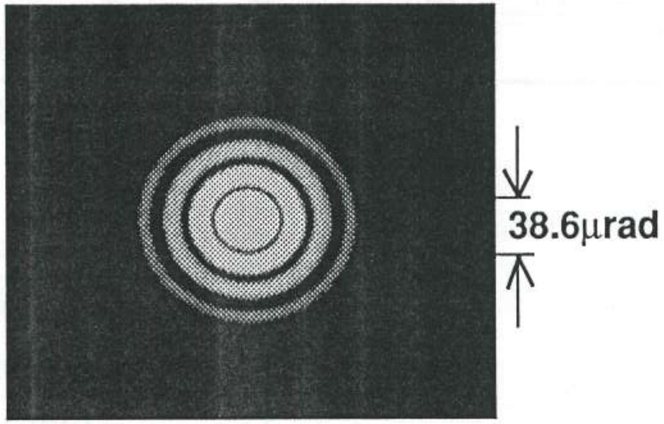
Features of Optical ISL and Required Simulating Functions

	Features of Optical Intersatellite Link	Simulating Functions
Intersatellite Laser Propagation	- Very Long Distance - Free-space Propagation - Existence of Backgound Noise	* Far-field Beam Pattern, Received Plane Wave, Attenuation and Propagation Time Delay * No Waveform Distortion * Incoherent Light Irradiation
Satellite Dynamics	- Attitute Variation and Gimbal Mechanism Noise - Uncertainty in Attitute and Position - Orbital Motion	* Variation in Beam Angle * Plane Wave Incidence from Arbitrary Direction * Optical Frequency Doppler-shift * Point-ahead

Free-space Simulator



Simulator Configuration



Measured Airy Pattern

Conclusions

1. Development of an IM/DD modem:

   10^{-9} BER, LD 100 mW output, -45 ~ -43 dBm
2. Using Etalon optical filter of 75 % reflectivity and surface accuracy of $\lambda/50$, we can reduce background noise to 1/10.
3. We developed beam tracking schemes robust to background noise using communication signal.
4. We obtained parameters of optical communication system required for stable bidirectional tracking and pointing operations.
5. We designed a free-space simulator for the laser transmission for laboratory experiment in order to simulate far field nature of optical wave transmission. This is a quite powerful tool for evaluation of tracking and pointing capability of onboard optical system.

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(2) Koji Yasukawa, Ken'ichi Araki, Kanshiro Kashiki and Tadashi Aruga, "Research and Development Activities of Optical ISLs in Japan", International Journal of Satellite Communications, Vol. 6, pp. 141-152, Mar. 1988.

(3) Ken'ichi Araki, Kanshiro Kashiki, Keizo Inagaki, Koji Yasukawa and Yoji Furuhama, "Interaction Characteristics of Two Coupled Tracking/Pointing Subsystems in Optical Intersatellite Communications", CLEO '88, TUY5, pp. 164-165, Anaheim, U.S.A., Apr. 1988.

(4) Koji Yasukawa, "Optical Intersatellite Links", Journal of the IEICE, Vol. 71, No. 5, pp. 468-470, May 1988.

(5) Masataka Mizushima, "Detection of Graviational Waves Applying the Technology of Intersatellite Communications", Journal of the IEICE, Vol. 71, No. 6, pp. 602-603, Jun. 1988.

(6) Koji Goto, Ken'ichi Araki and Koji Yasukawa, "Etalon Filter Applicable to Optical Intersatellite Communications", OSA Annual Meeting, FAA1, pp. 181-182, Santa Clara, U.S.A., Nov. 1988.

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(8) Koji Yasukawa, "Research and Development of Basic Technologies for Optical Intersatellite Link", Review of Laser Engineering, Vol. 17, No. 9, pp. 628-634, Sep. 1989.

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(10) Koji Yasukawa, Koji Goto, Kanshiro Kashiki, Ken'ichi Araki, Masaru Nagai and Motoh Shimizu, "Configuration and Performance of Optical Modulator/Demodulator for Optical Intersatellite Communications", OE/LASE '90, 1218-33, pp. 348-354, Los Angeles, U.S.A., Jan. 1990.

(11) Ken'ichi Araki, Keizo Inagaki and Koji Yasukawa, "Design of Compact Transceiver Optical Systems for Optical Intersatellite Links", OE/LASE '90, 1218-17, pp. 169-177, Los Angeles, U.S.A., Jan. 1990.

(12) Koji Goto, Ken'ichi Araki and Koji Yasukawa, "Effects of Antenna Pointing Errors on the Design of Heterodyne Optical Intersatellite Communications", Trans. IEICE B-II, Vol. J73-B-II, No. 6, pp. 279-285, Jun. 1990.

(13) Koji Goto, Ken'ichi Araki and Koji Yasukawa, "Etalon Filter for Direct Detection Receiver in Optical Intersatellite Communications", Trans. IEICE B-II, Vol. J73-B-II, No. 7, pp. 319-327, Jul. 1990.

◦ 昼間　可能.
◦ 前より / 3dB optical path
これから対策する

◦ LDは AlGaAs. NEC.

◦ #13.

1-4

Laser communication experiment using Japan's engineering test satellite-VI

Ken'ichi Araki
Motokazu Shikatani
Masahiro Toyoda
Tadashi Aruga

Communications Res. Lab., MPT

IWOSC '90
December 6 and 7, 1990, ATR, Kyoto

Laser Communication Experiment Using Japan's Engineering Test Satellite-VI

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Communications Research Laboratory (CRL, Ministry of Posts and Telecommunications, Japan) has been engaged in development of three advanced satellite communication payloads aiming at experiments using Japan's 2-ton class Engineering Test Satellite VI (ETS-VI) which is to be launched into geostationary orbit by NASDA in August 1993. The CRL's three experimental systems are (1) S-band intersatellite communications, (2) millimeter-wave intersatellite and personal-satellite communications, and (3) optical intersatellite communications.

An experimental space optical communication system is designed to conduct several fundamental experiments for the future intersatellite optical communication. These are, 1) high-precision tracking, 2) dual-link optical communication, 3) high accuracy attitude measurement, 4) point-ahead angle verification test, 5) laser beam propagation measurement, and 6) optical device tests in space. The onboard system with a 75 mm diameter telescope weighs only about 20 kg and has fundamental functions required for space optical communications with coarse and fine tracking mechanisms, a laser diode transmitter, a laser beam point-ahead mechanism, a Si-APD receiver, a modulation /demodulation subsystem, and so on. A flight model of the onboard system is under development and will be completed in the first half of 1991.

A new optical facility used for a fixed ground station (in CRL) was constructed in 1989 for multi-purpose studies which include 1) satellite tracking, 2) laser ranging, 3) optical communication, 4) astronomy, 5) laser rader, and 6) radiometry. Preliminary experiments are made for the ground tracking/ pointing system by both optical observations of and laser beam transmission to geostationary orbit satellites.

Author Biography:

Ken'ichi ARAKI

Dr. Araki joined Radio Research Laboratory, the Ministry of Posts and Telecommunications in 1982, where he worked on the development of optical systems for space science and engineering. He was with ATR Optical and Radio Communications Research Laboratories from May 1987 to March 1990. He was engaged in the research of optical beam control and its relating optics for optical intersatellite link communications. He is currently with Communications Research Laboratory, the Ministry of Posts and Telecommunications. Now he is engaged in the development of a laser communication equipment which will be experimented in the Japan's engineering test satellite (ETS)-VI.

He received the B.S., M.S. and Dr. Eng. degrees in electrical engineering from Tohoku University, Sendai, Japan in 1973, 1975 and 1980, respectively. He is a member of the Optical Society of America and the Institute of Electronics, Information and Communication Engineers (IEICE).

Laser Communication Experiment Using Japan's Engineering Test Satellite-VI

K. ARAKI, M. SHIKATANI, M. TOYODA,

and T. ARUGA

Communications Research Laboratory
Ministry of Posts and Telecommunications

TOKYO, JAPAN

IWOSC '90, December 6 at ATR

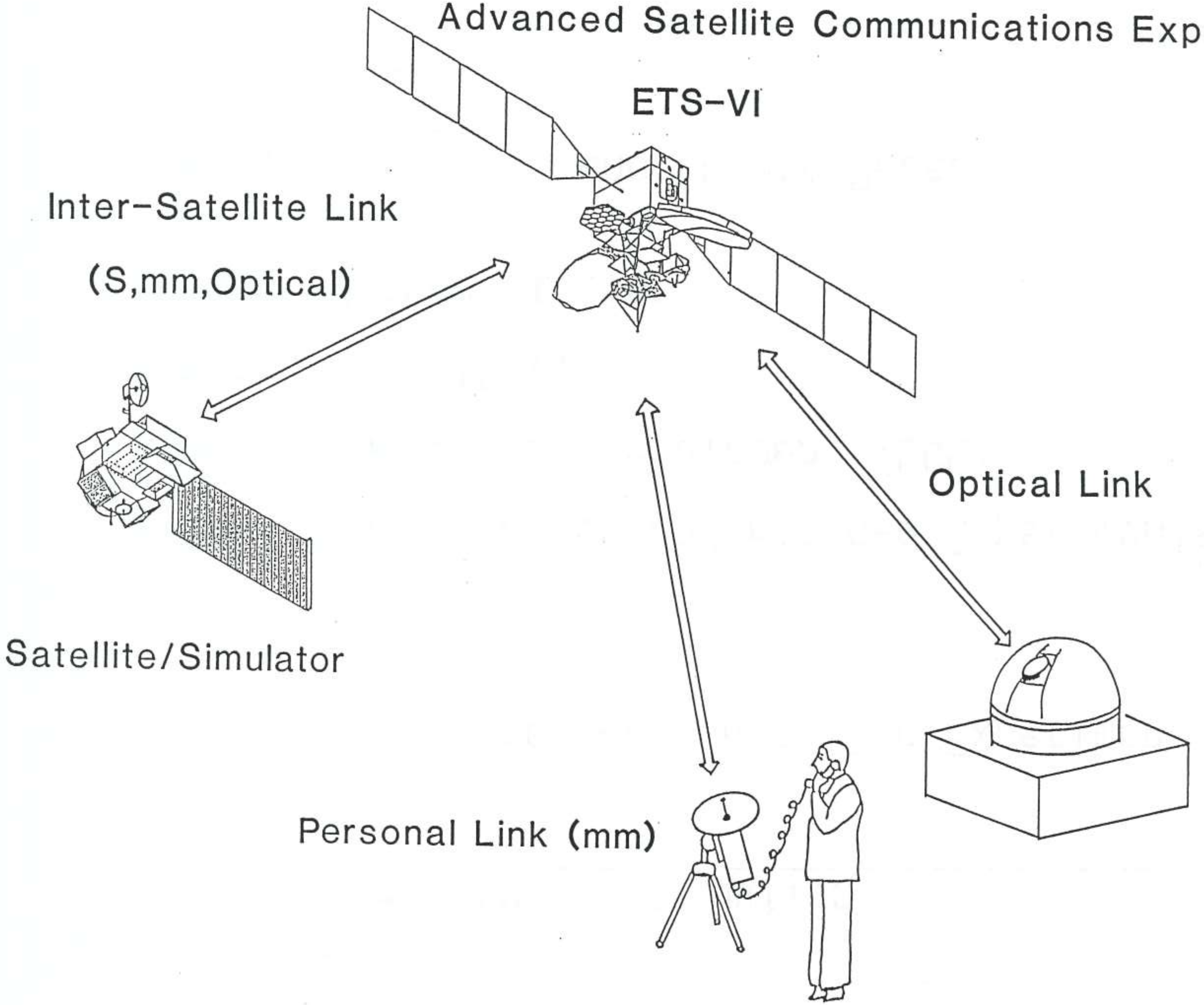
Presentation Outline

1. Objectives of Laser Communication Experiment

2. Experiment System Definition
   - ·System Configutation and Planned Experiments
   - ·Laser Communication Equipment (LCE) onboard the ETS-VI
   - ·Optical Ground Station

3. Development Status and Future Research

Advanced Satellite Communications Experiment



ETS-VI

Inter-Satellite Link

(S,mm,Optical)

Satellite/Simulator

Optical Link

Personal Link (mm)

Engineering Test Satellite-VI (ETS-VI)

Launch Date	Summer, 1993
Launch Vehicle	H-II
Spacecraft Mass	Around 2 tons (Initial weight in geostationary orbit)

Purpose

* Verification of H-II launch vehicle performance

* Establishment of bus technologies for a two-ton class three-axis stabilized geostationary satellite

* Technological development and experiments on advanced satellite communications

Advanced Satellite Communications Experiment Using ETS-VI

(Communications Research Laboratory, MPT)

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1 . S band Inter-Satellite Communications

* Phased-Array Multibeam Data Relay Experiments
* Inter-Operable Data Relay and Tracking System

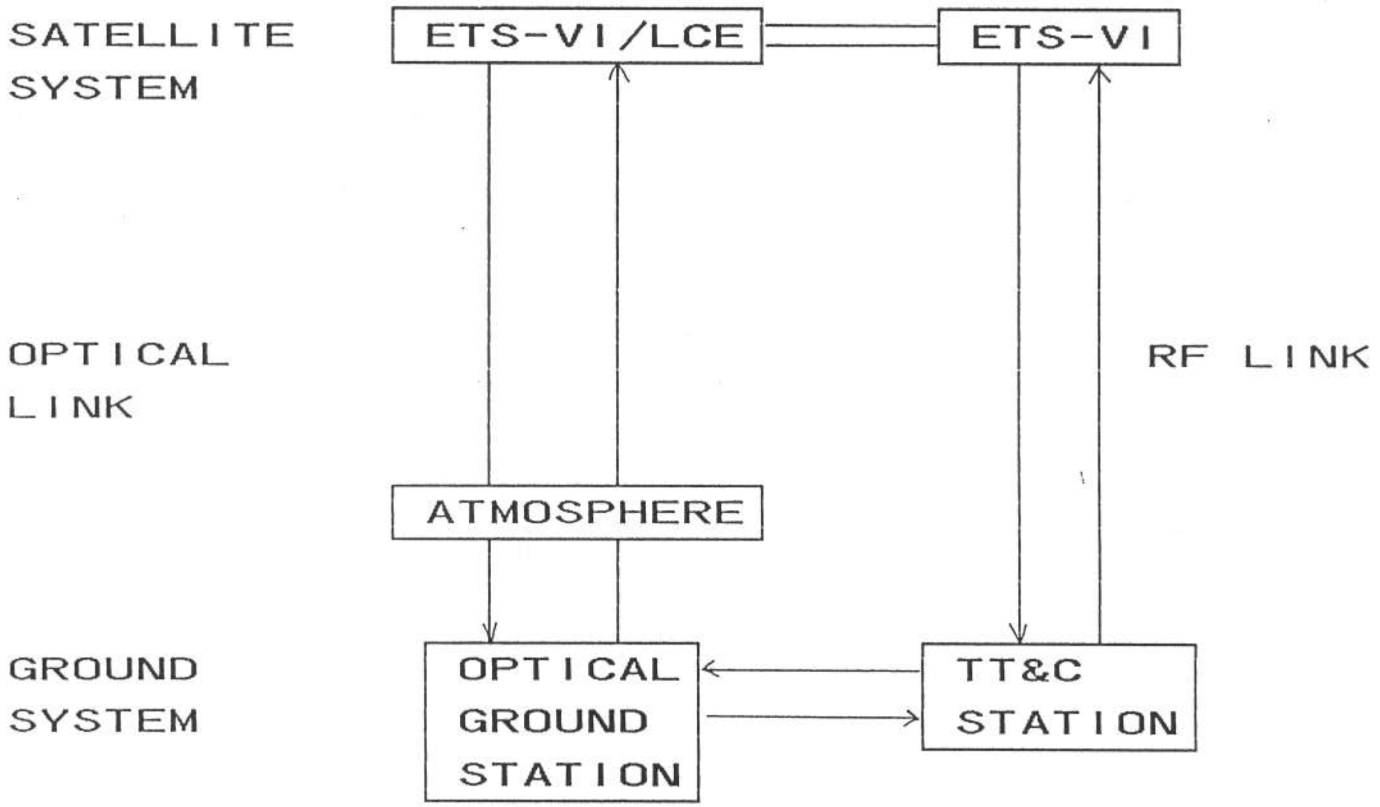
2 . Millimeter-Wave Satellite Communications

* Millimeter-wave Inter-Satellite Communications
* Millimeter-wave Personal Satellite Communications
* 43/38 GHz

3 . Basic Optical Communications Experiment

* Laser Beam Tracking and Pointing Experiments
* Optical Satellite Communications
* 0.51/0.83 micron

Laser Communication Experiment System



OBJECTIVES OF THE ETS-VI BASIC OPTICAL COMMUNICATION PROGRAM

(a) the establishment of the basic technology for an optical satellite communication system

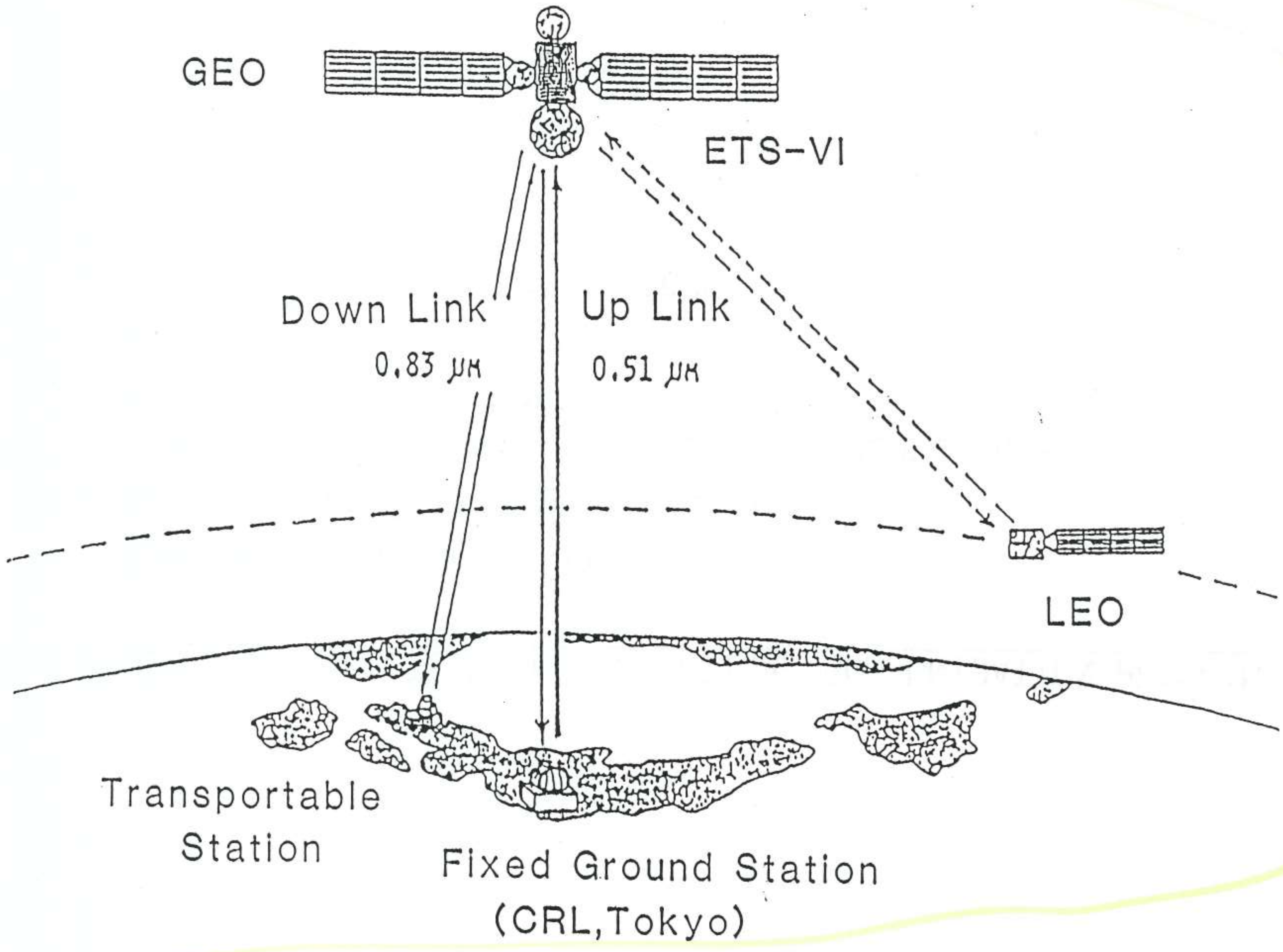
(b) to perform miscellaneous scientific studies using the onboard optical transmitter/receiver equipment.

(c) the analysis of optical device performance in the space environment

EXPERIMENTS OF THE ETS-VI BASIC OPTICAL COMMUNICATION PROGRAM

1. High precision tracking
2. Dual link optical communication
3. High accuracy satellite attitude measurements
4. Point-Ahead angel test
5. Laser beam propagation
6. Optical device tests in space

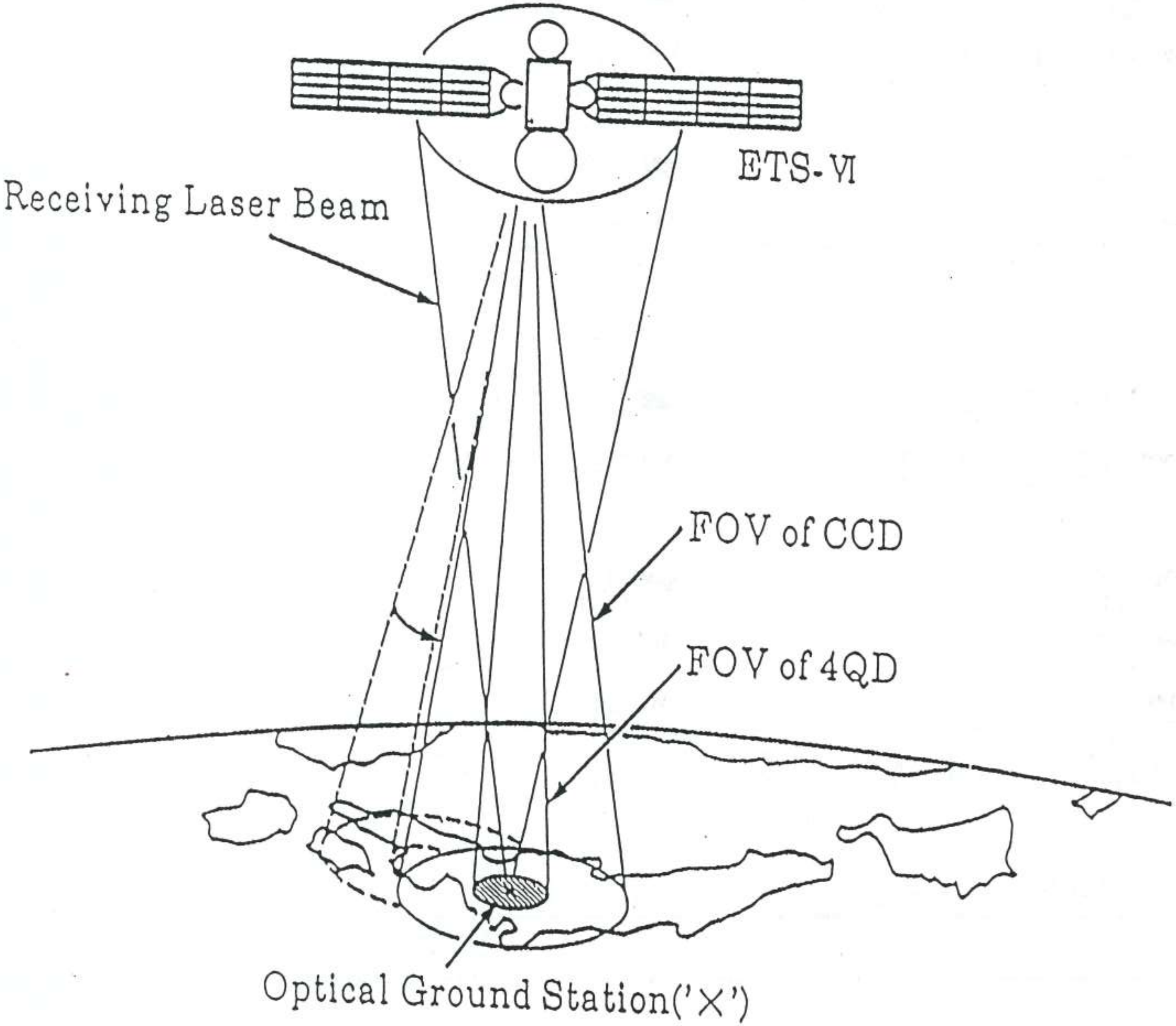
ETS-VI Optical Satellite Communication



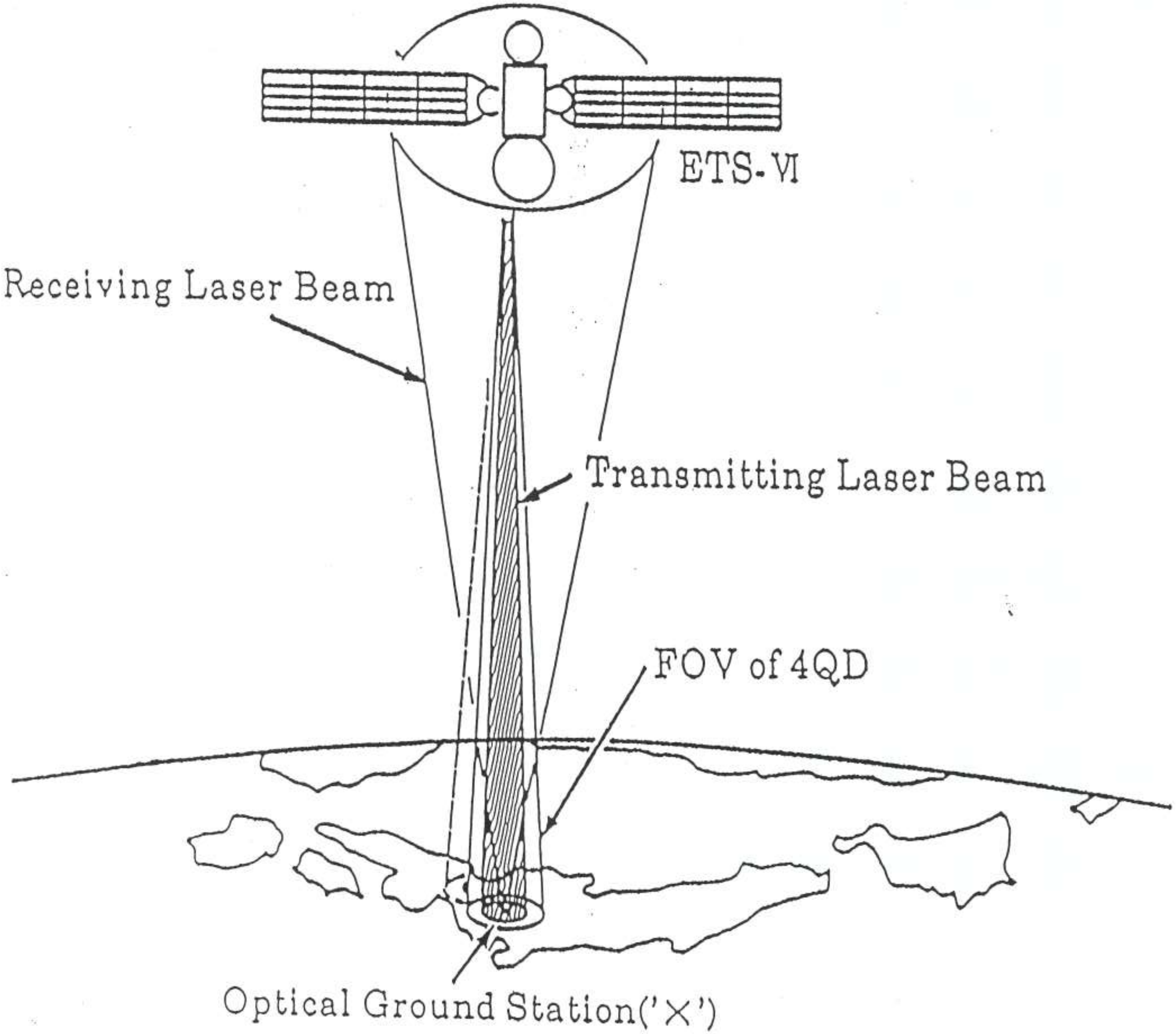
L C E Link Budget

	Up Link	Down Link
Transmitter		
Power(Ave) 4 W	36.0 dBm	13.8 mW 11.4 dBm
Loss	-4.0 dBm	-5.8 dBm
ANT Gain	109.0 dBm	105.5 dBm
Miss Point Loss	-3.0 dBm	-1.5 dBm
Space Loss	-299.3 dBm	-295.2 dBm
Atomospheric Loss	-3.0 dB	-3.0 dB.
Receiver		
ANT Gain 7.5 cm / 1.5 m	113.2 dBm	1.5 m 135.0 dBm
Loss	-11.0 dB	-1.7 dB
Received Power	-62.1 dBm	-58.0 dBm
Margin	0.1 dB	2.7 dB

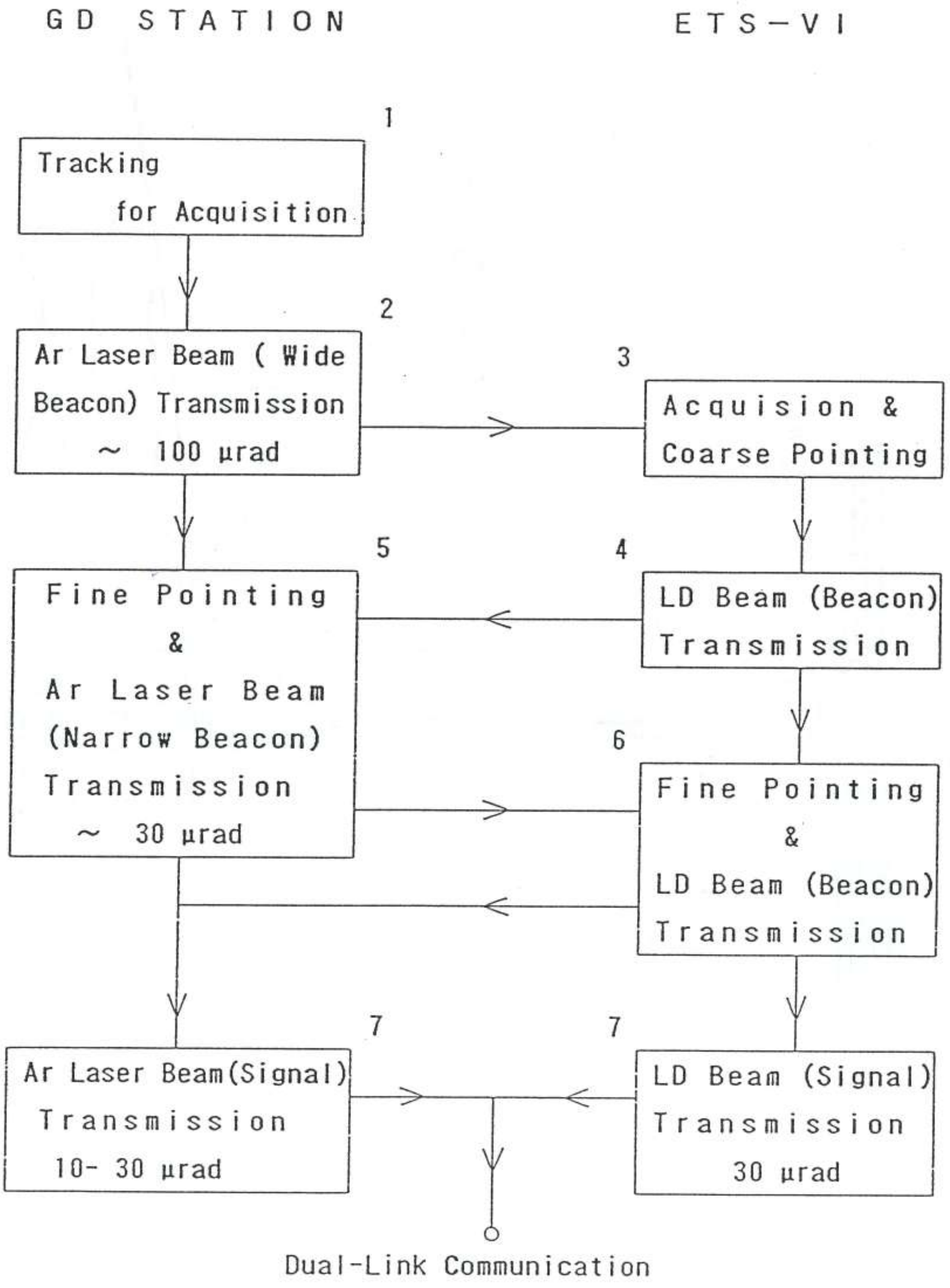
Acquisition/Coarse Tracking Experiment



Fine Pointing Experiment



STEPS OF OPTICAL LINK FORMATION AND COMMUNICATION



Note: Ar laser 0.5145 μm, LD 0.83 μm

LCE Key Function

(a) Transmitting and receiving of laser beams

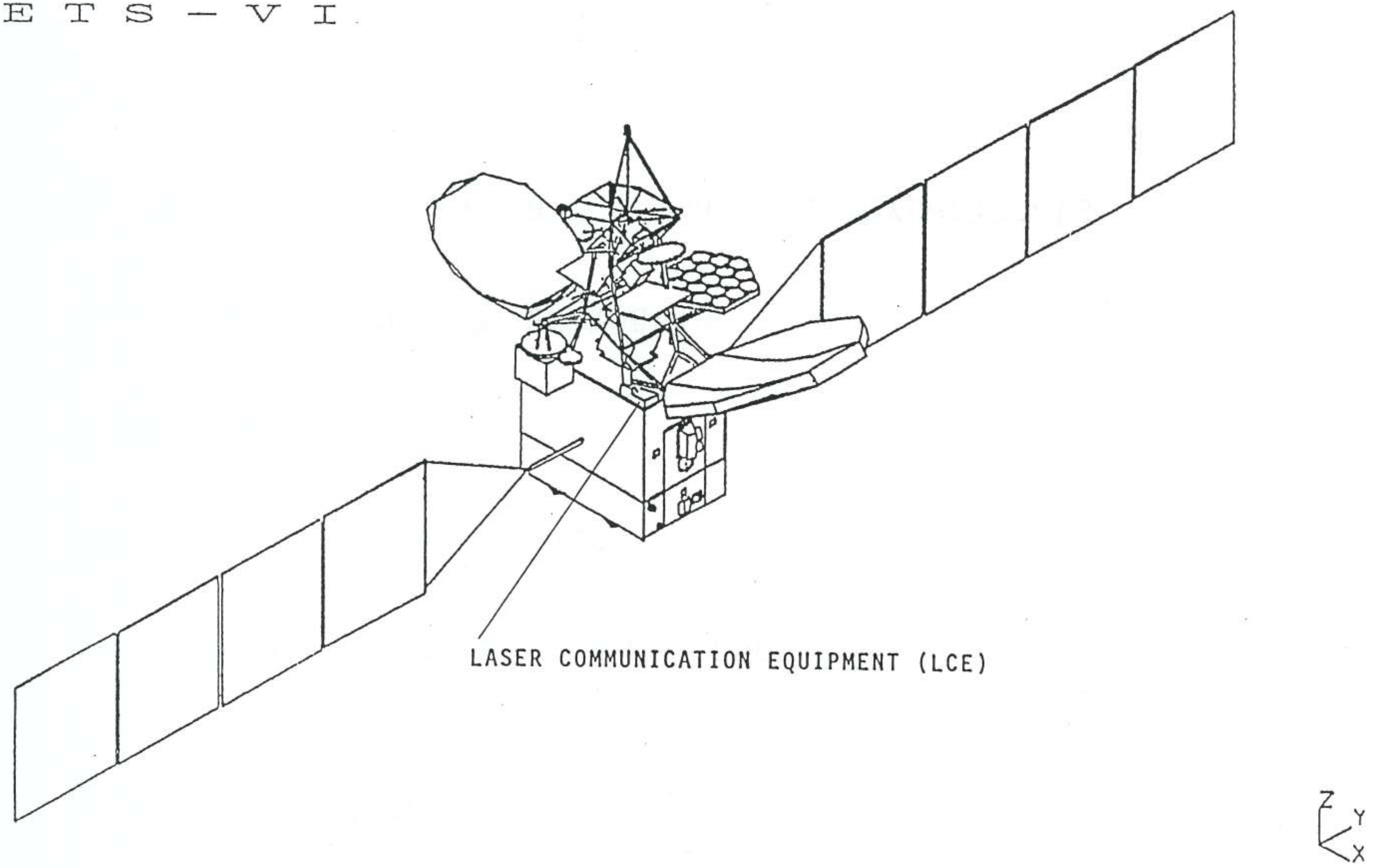
(b) High -precision beam control

(c) Point ahead angle

(d) Satellite attitude determination

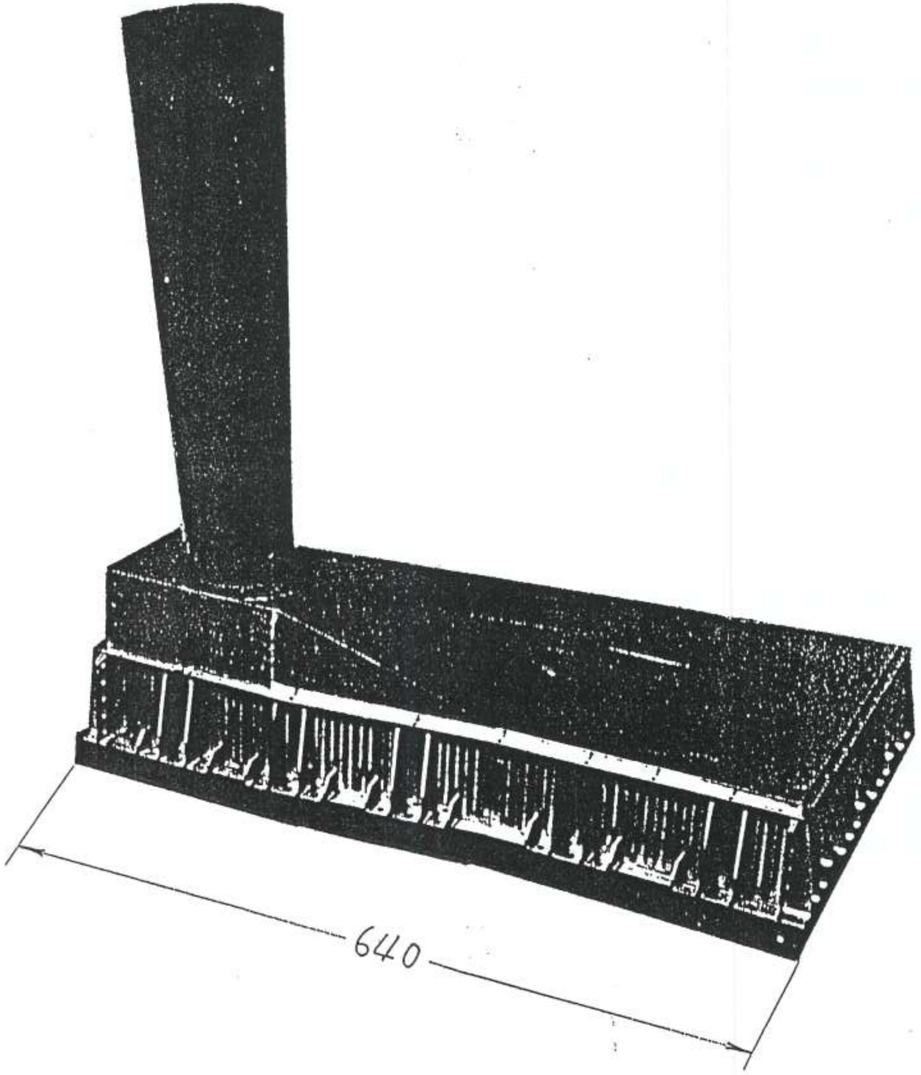
(e) Optical communication and propagation experiments

ETS - VI



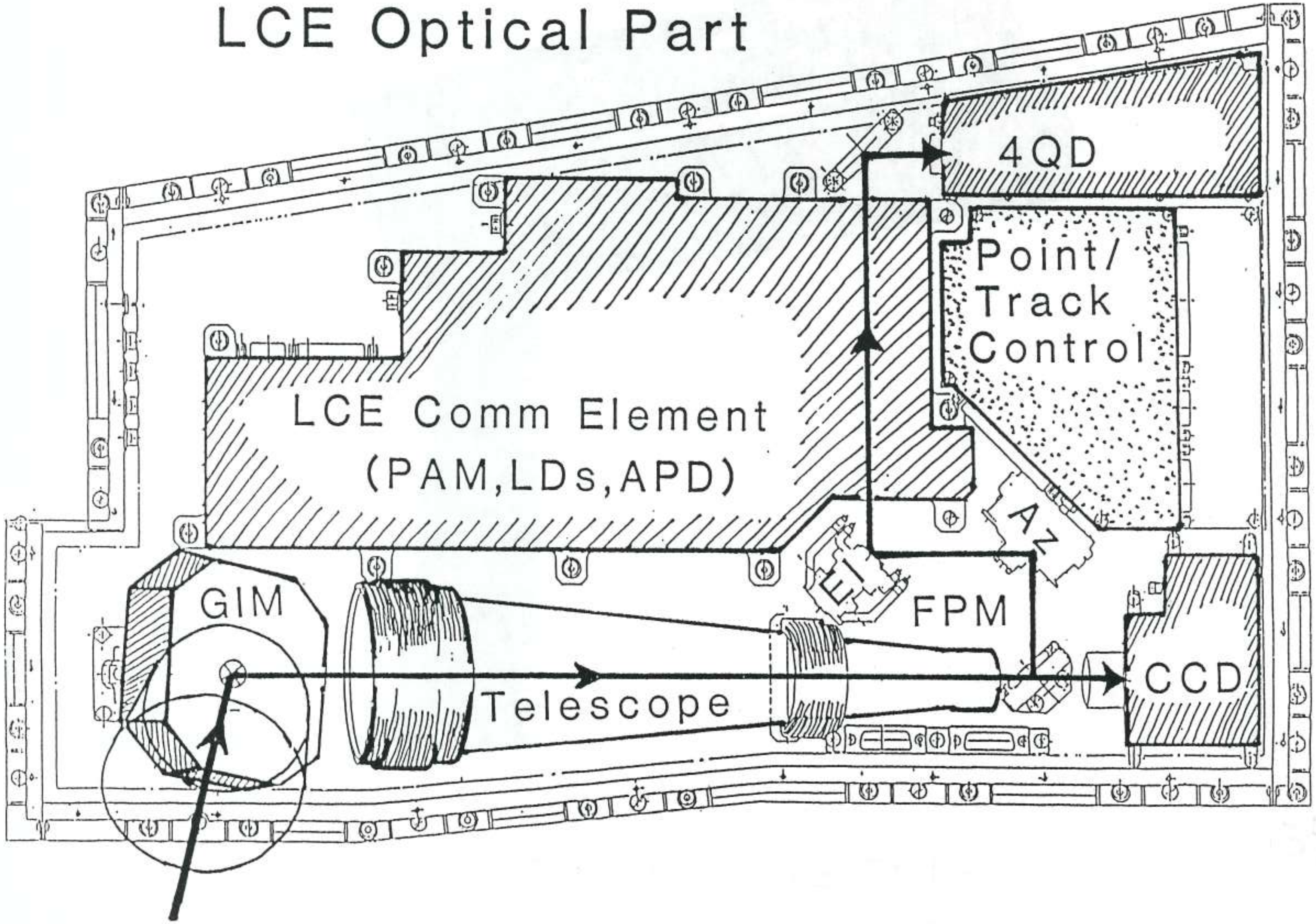
OUTSIDE VIEW OF LCE-O

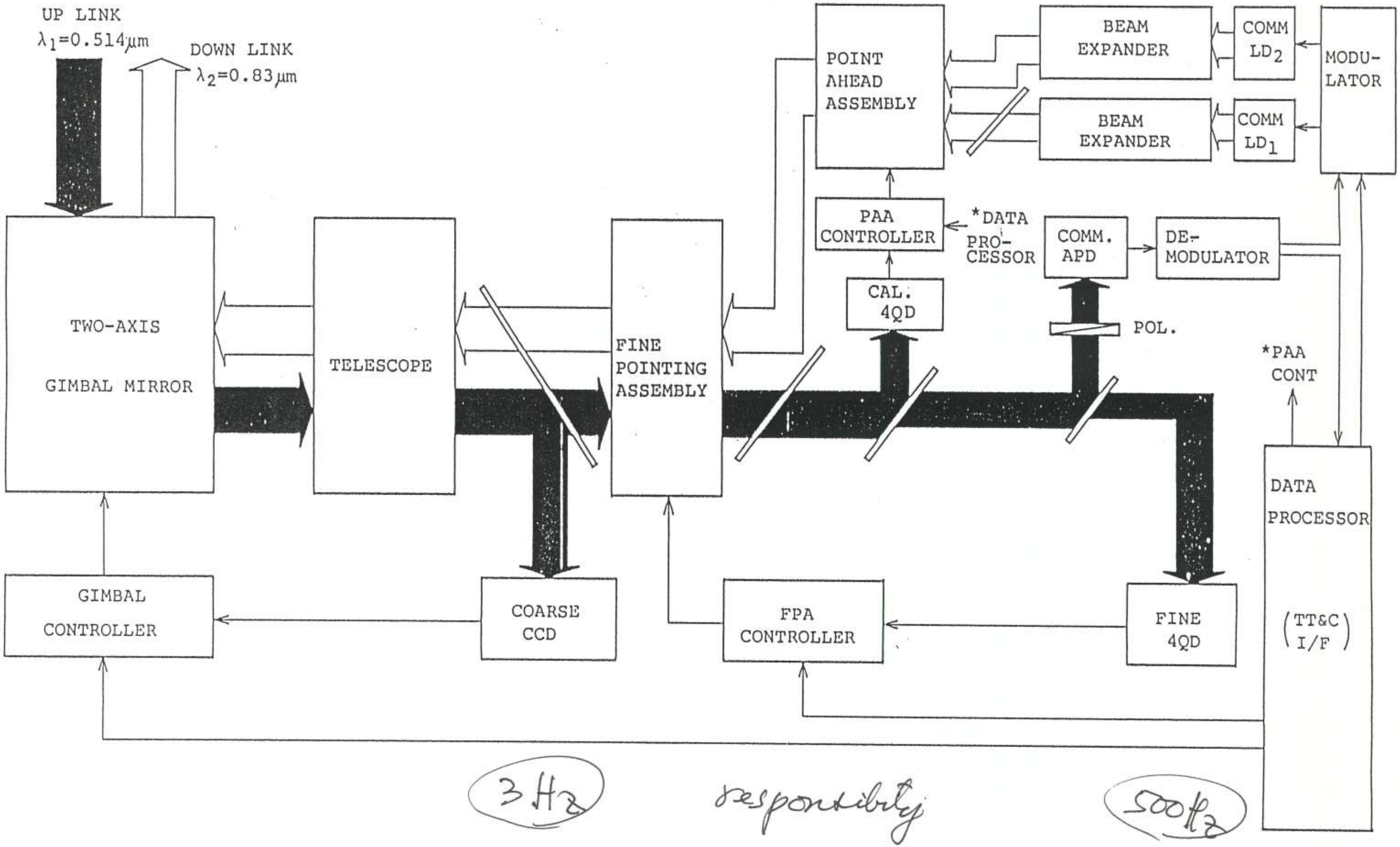
13kg.



(Scale: in mm)

LCE Optical Part





3 Hz

responsibilty

500 Hz

LCE SYSTEM BLOCK DIAGRAM

Space Optical Communication Equipment

Major Specifications of the LCE

Total Weight:	21.8 kg
Power Consumption:	81.0 W
Telescope Diameter:	7.5 cm
Magnification:	x 15

Transmitting Part

Laser:	L D (AlGaAs)
Wave Length:	0.83 μ m
Average Power:	13.8 mW
Beam Divergence:	30/60 μ rad.
Data Rate:	1.024 Mbps
Modulation:	Intensity (Manchester Coding)

Pointing Part

Coarse Pointing Subsystem

Detector:	C C D
Acquisition Range:	±1.5 deg
Field of View:	8 mrad
Actuator:	Two-Axis Gimbals

Fine Pointing Subsystem

Detector:	4 Q D
Field of View:	0.4 mrad

Receiving Part

Detection Band:	0.51 μ m(Argon)
Detector:	APD(Direct Det)
Data Rate:	1.024 Mbps

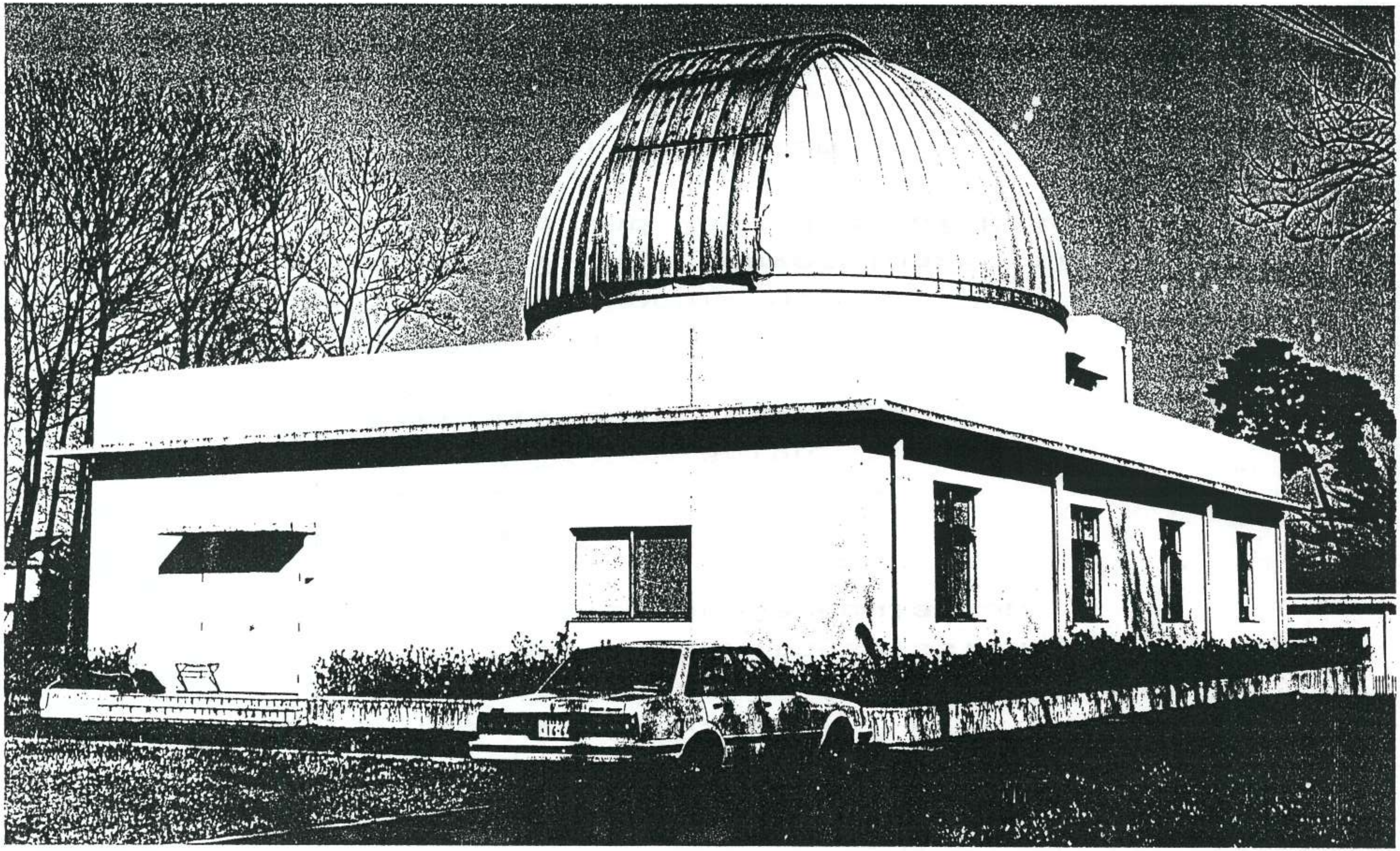
Optical Ground Station

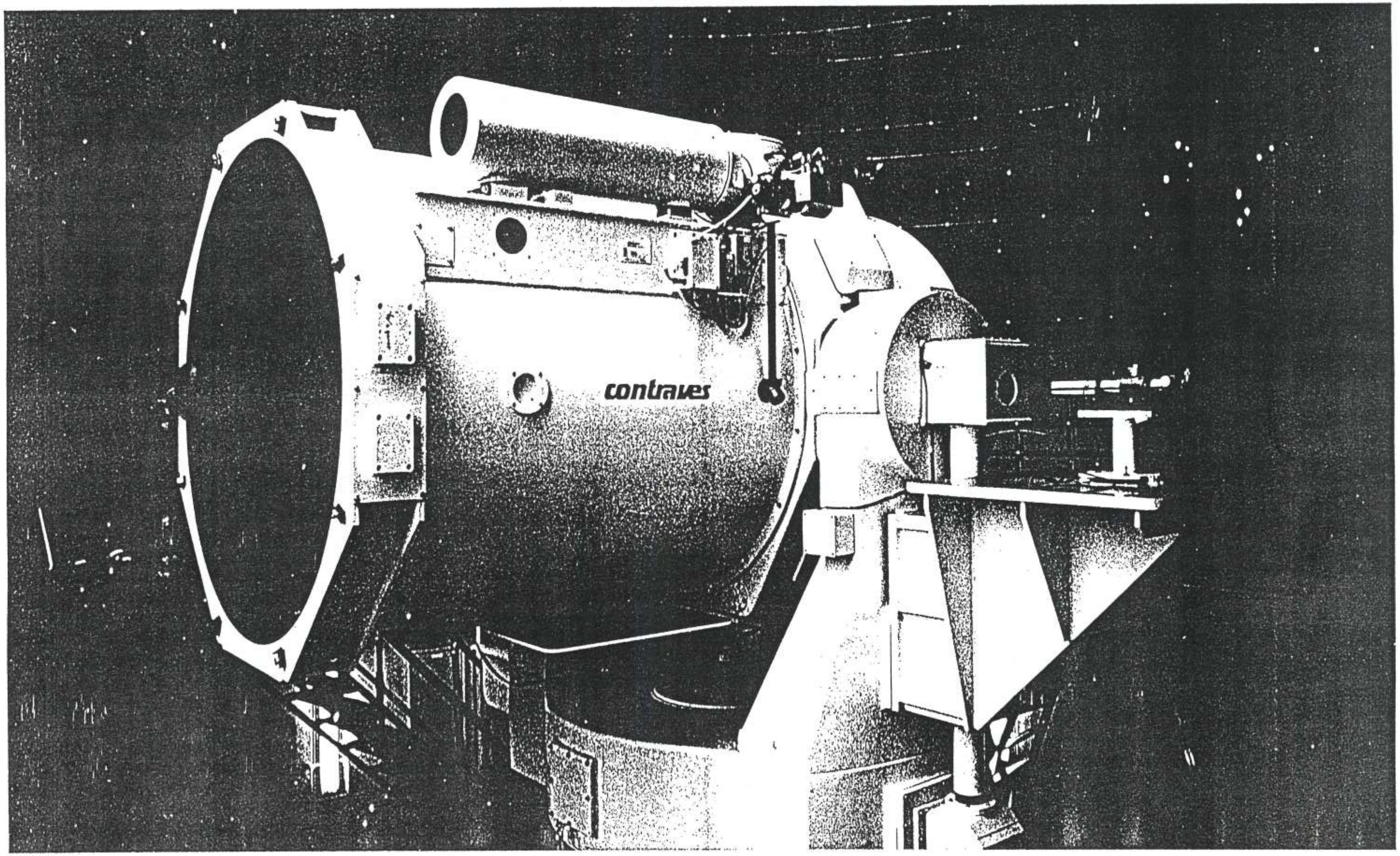
- Laser Transceving System
  - Instrument Pointing System Control
  - Laser Modulation/Transmission
  - Laser Receiption/Demodulation

- TT&C Sub-Station
  - Command Data Generation
  - Command Transmission
  - Telemetry Data Receiption

- Data Recorder/Analyzer
  - Experiment Recording
  - Telemetry Data Conversion/Edition
  - Analyzing and Recording of Results

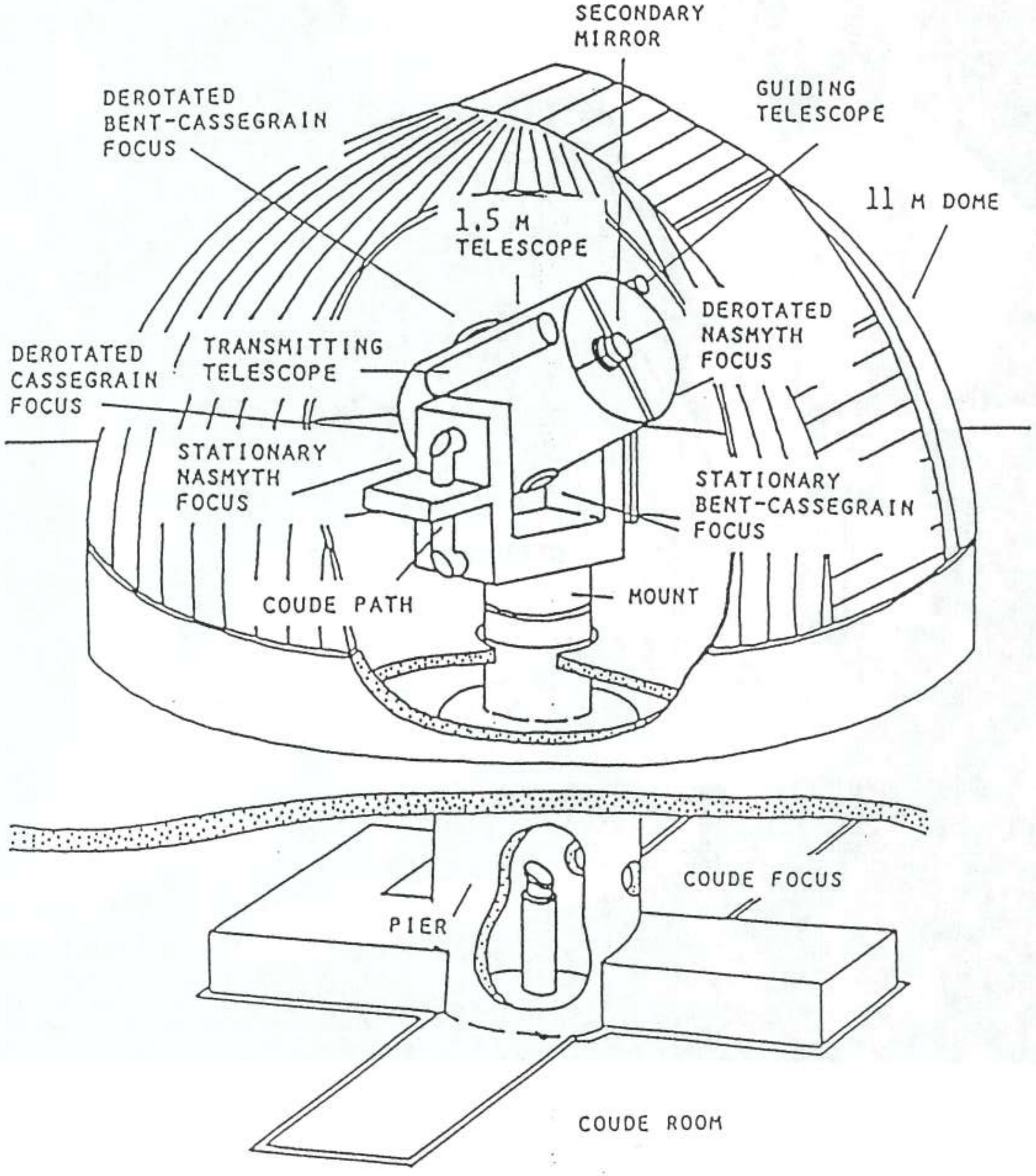
- Calibration/Utility System
  - Orbit Determination
  - Weather Monitoring
  - Mount Model Generation





contraves

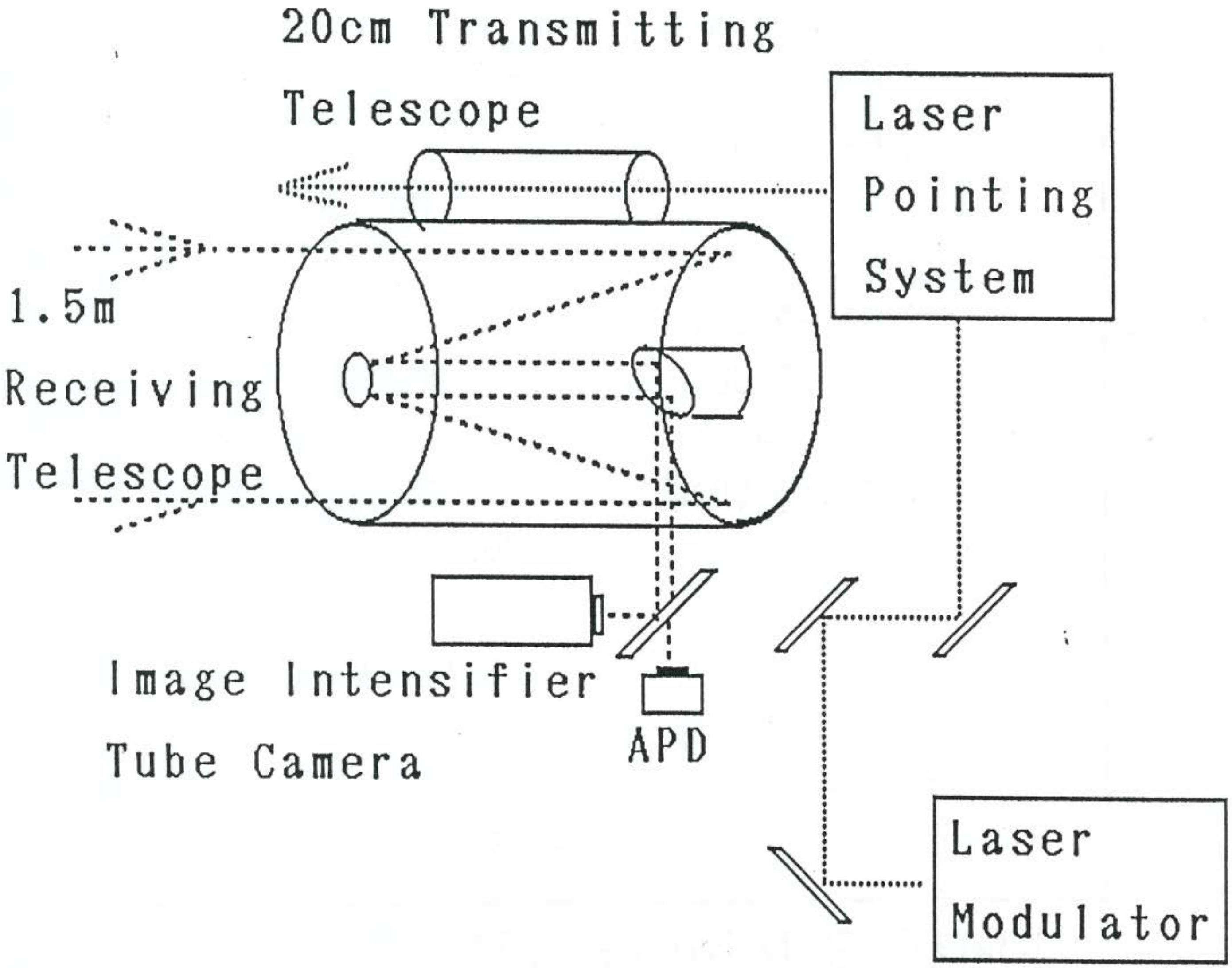
CRL Optical Ground Station



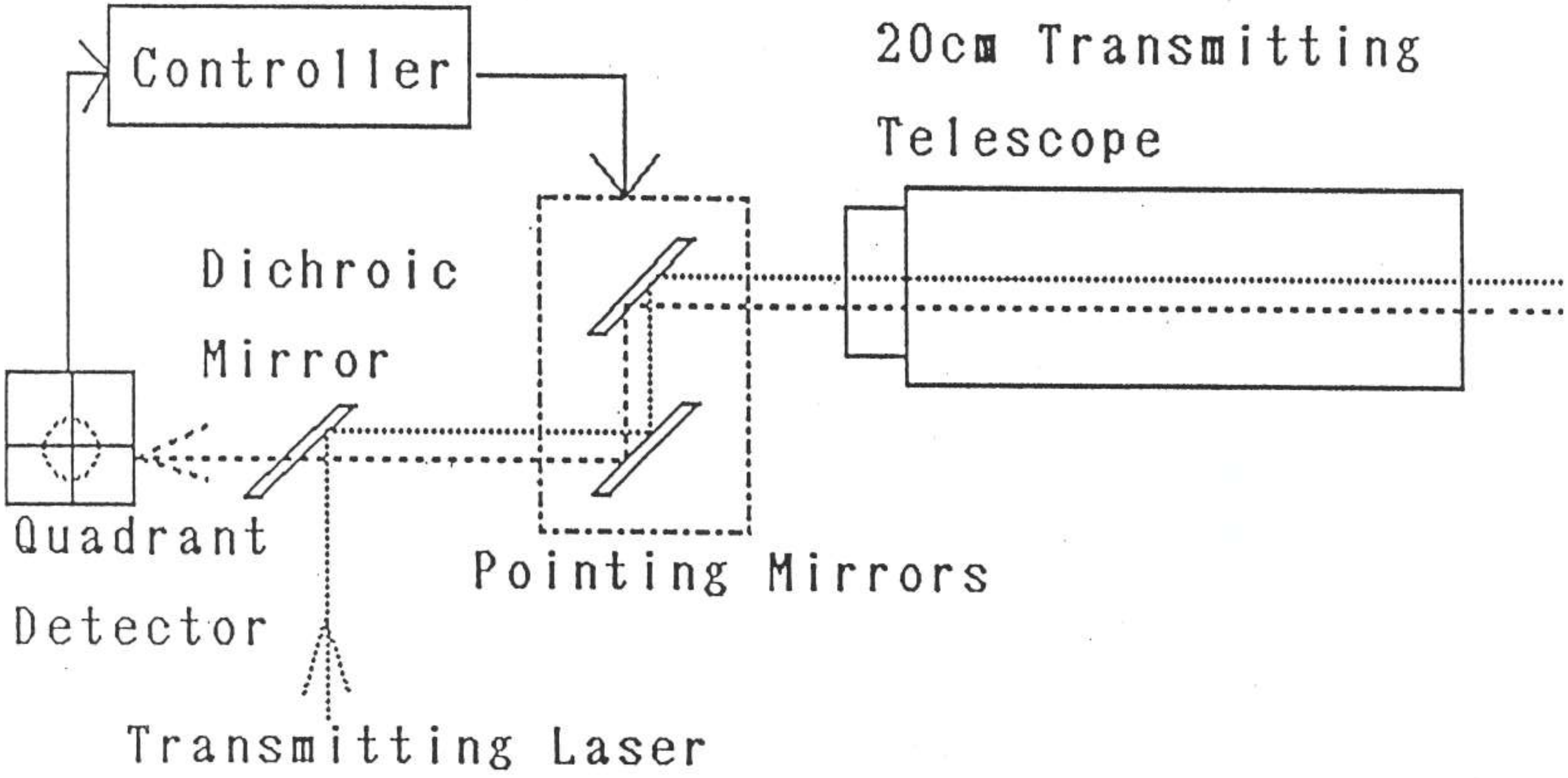
CRL Optical Ground Station

Transmitting telescope	
Mirror design	Off-axis Marsenne
Aperture	20 cm
Expantion ratio	10
Receiving telescope	
Mirror design	Bent Cassegrain
Aperture	1.5 m
Focal length	2.25 m
Surface figure	<1.0 arc-sec
Mount and control	
Structure	AZ/EL gimbal
AZ-EL perpendicularcy	0.1 arc-sec
Encoder resolution	0.0001 deg
Tracking velocity	Max. 15 deg/sec (AZ) 5 deg/sec (EL)
Tracking accuracy	1 arc-sec

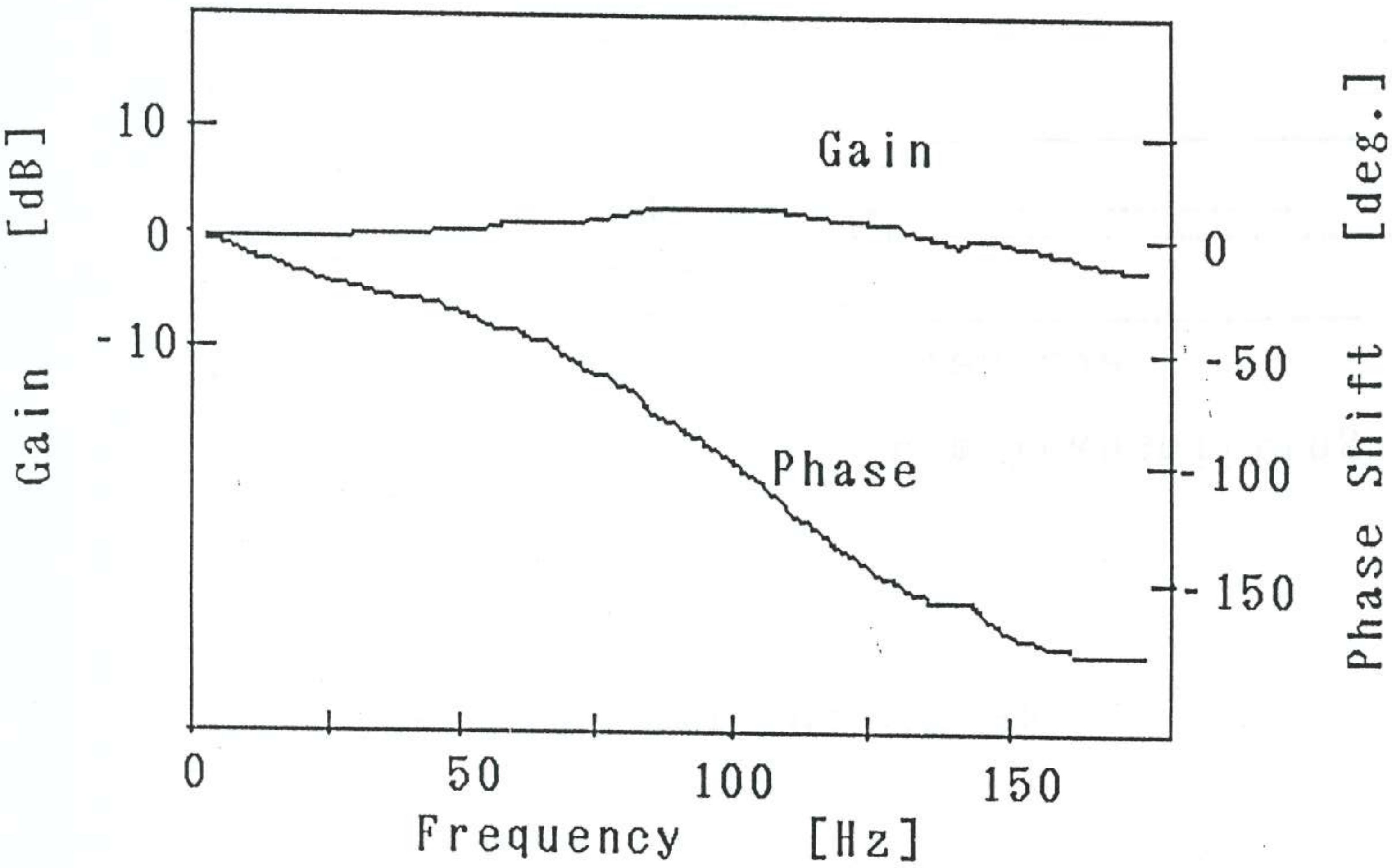
Optical Communication Equipment



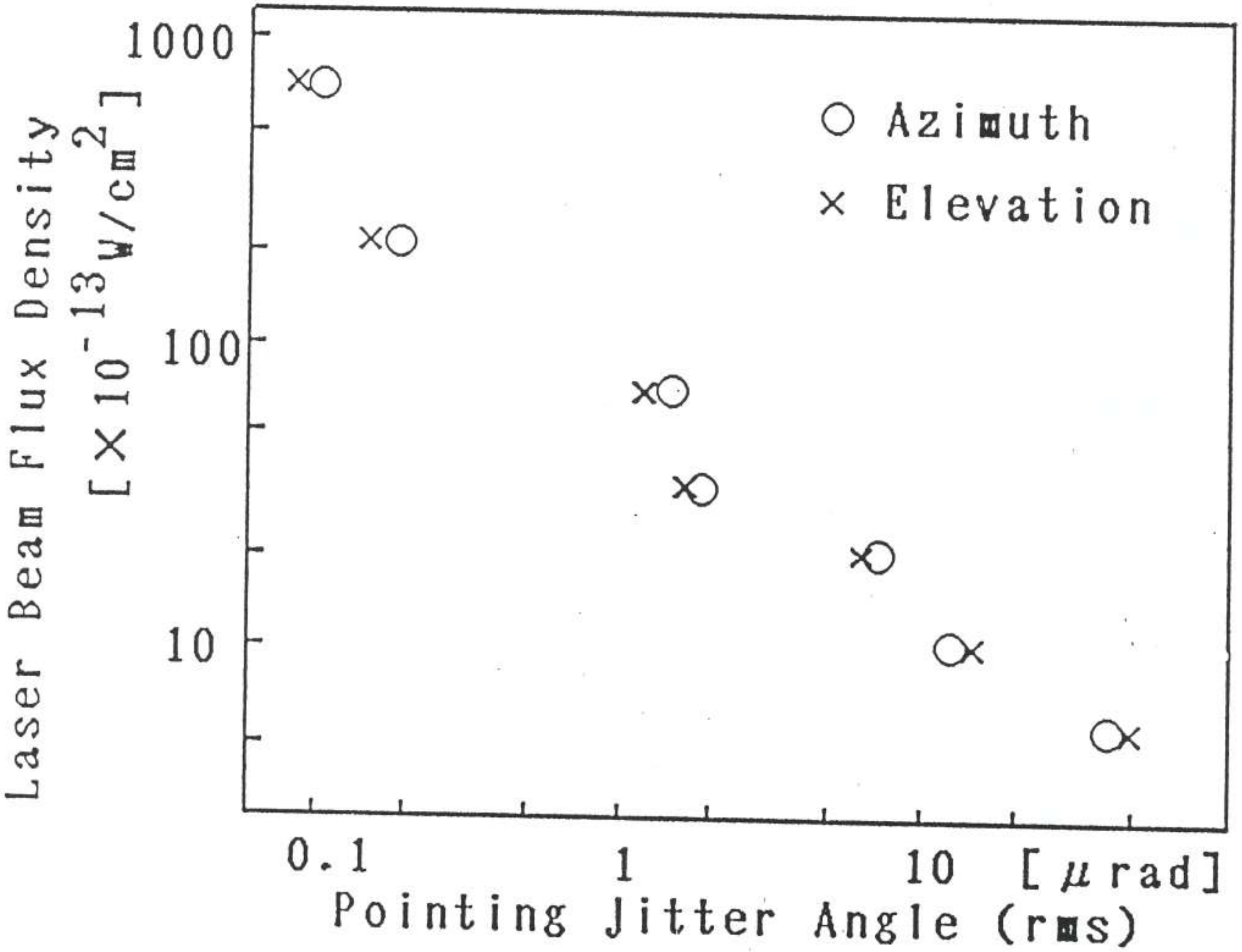
Laser Transmitting System



Frequency Characteristics of
Closed Loop Pointing System



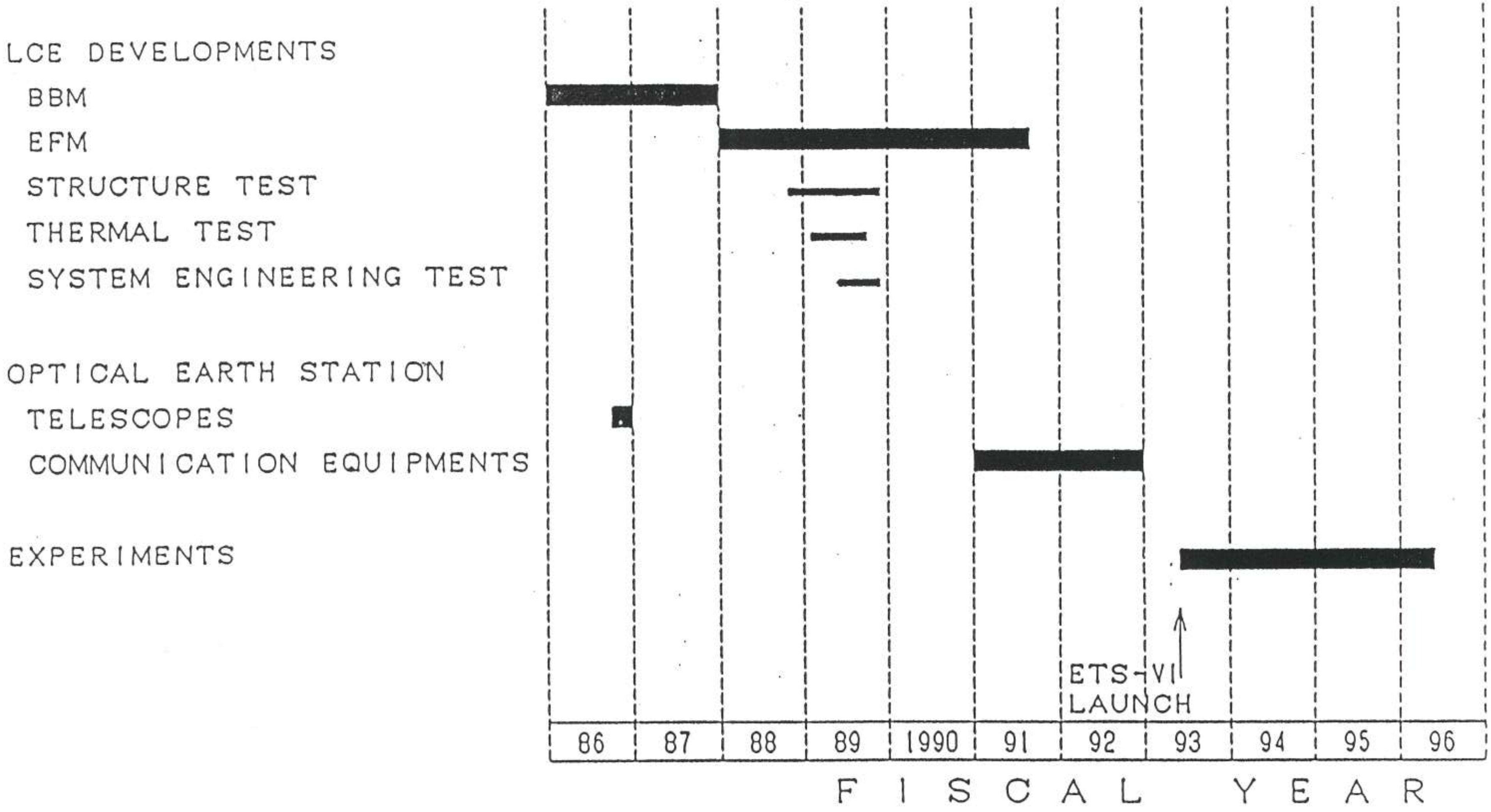
Received Laser Flux Density versus Pointing Jitter Angle



Atmospheric Effects

- Intensity Fluctuation
    - Frequency (Fade Duration)
    - Amplitude (Surge/Fade Depth)
- Beam Wandering (Uplink/Downlink)
    - Frequency
    - Amplitude
- Absorption
    - Path Condition (Dry/Hazy)

Development and experiments schedule of the optical satellite communication project.



JSAT-2 152°E.
ETS-VIと軌道が近い。

Future Research

- Improvement of Ground Optical System
- Optical Tracking of Stars and Satellites near the ETS-VI Orbit
- Laser Beam Transmission to Satellites such as GMS

up-link
数100μrad.

1-5

Recent developments in intersatellite laser communication technologies at NASDA

Hiroshi Arikawa

NASDA
Tsukuba Space Center

IWOSC '90
December 6 and 7, 1990, ATR, Kyoto

RECENT DEVELOPMENTS IN INTERSATELLITE LASER COMMUNICATION TECHNOLOGIES AT NASDA

Hiroshi Arikawa
Tsukuba Space Center
National Space Development Agency of Japan (NASDA)
Tsukuba-city, Japan

ABSTRACT

National Space Development Agency of Japan (NASDA) has been studying and developing an intersatellite laser communication (ILC) system and plans ILC experiments in space.

There are many technical matters to be investigated in order to realize lasercom in space. The acquisition, tracking and pointing (AT&P) technology , which aims to establish and maintain lasercom link in space, and the highly reliable laser transmitter with high power are especially very important.

NASDA began the system study for ILC in 1985 and schedules the research and development of ILC systems to meet a plan of performing ILC experiments in space between Japanese Experimental Module (JEM) and Data Relay and Tracking Satellite (DRTS) in 1998. And NASDA started to fabricate and evaluate trial models of principal constituents in AT&P subsystem since 1987.

The ILC study in NASDA is performed in two phases , that is a future ILC system and an experimental ILC system. The future system will be designed to satisfy data transmission requirements of high speed and large capacity and will become one of the most important transmission carrier of the space communication network infrastructure. The experimental system is the present target of the ILC research and development.

The experimental system is intended to evaluate and to establish the AT&P technology for optical link between satellites in GEO and LEO.

The AT&P subsystem is to be divided into three assemblies, that is a coarse pointing assembly (CPA) which performs initial acquisition, coarse acquisition and tracking of the beam from the target satellite, a fine pointing assembly (FPA) which performs fine acquisition and tracking of the beam from the target satellite and a point-ahead assembly (PAA) which steers a point-ahead correcting mirror to point transmitting beam at the receivable location of the target satellite.

The ILC system needs to satisfy the highly precise requirement of a fine tracking pointing error of about ±1 μrad or less when it adopts a transmitting lasercom beam with the beam divergence of about 10 μrad or less. In addition, a wide tracking range (±15 deg in GEO, ±180 deg in LEO) is required in the case of GEO-LEO ILC link, because of their individual orbits.

The requirement of the point ahead accuracy needs to satisfy the value at least equivalent to the fine pointing accuracy of ±1 μrad or less.
And the point ahead pointing range of ±75 μrad or more is required.

NASDA has fabricated two trial models of the AT&P subsystem, which adopt different methods respectively, one is called method-A and the other method-B .

The trial AT&P model of method-A uses a combination of a direct drive motor as a coarse pointing driver, a multi-layered piezo-electric actuator as a fine pointing mirror deflector and also a multi-layered piezo-electric ceramic actuator as a point-ahead correcting mirror deflector.

The AT&P subsystem of method-B uses a combination of a stepping motor with a harmonic drive as a coarse pointing driver, a moving coil type actuator as a fine pointing mirror deflector and also a torsion bimorph type piezo-electric actuator as a point-ahead correcting mirror deflector.

The result of the trial fabrication of both methods satisfies the target tracking performance of ±1 μrad or less. We have a prospect to realize an AT&P subsystem which meets the requirements of the ILC system. Following this fabrication, NASDA is going to develop research models of the ILC system.

Hiroshi Arikawa was born in Mie Prefecture, Japan in 1946. He received the B. S. degree in electronic engineering from Shizuoka University, Shizuoka, Japan, in 1969.

In 1969, he joined Japan Broadcasting Corporation (NHK). He has been working in National Space Development Agency of Japan (NASDA) since 1988. He is currently engaged in the research & development of intersatellite laser communication.

Recent Developments in Intersatellite Laser Communication (ILC) Technologies at NASDA

Hiroshi Arikawa

Equipment and Parts Development Department
Tsukuba Space Center
NASDA

1990.12.6

PRTS
1998

- Intersatellite Laser Communication (ILC) system is under research and developing at NASDA
- The purpose of developing ILC system is ;

(1) To make Intersatellite communication equipment compact, lightweight and low power consumption

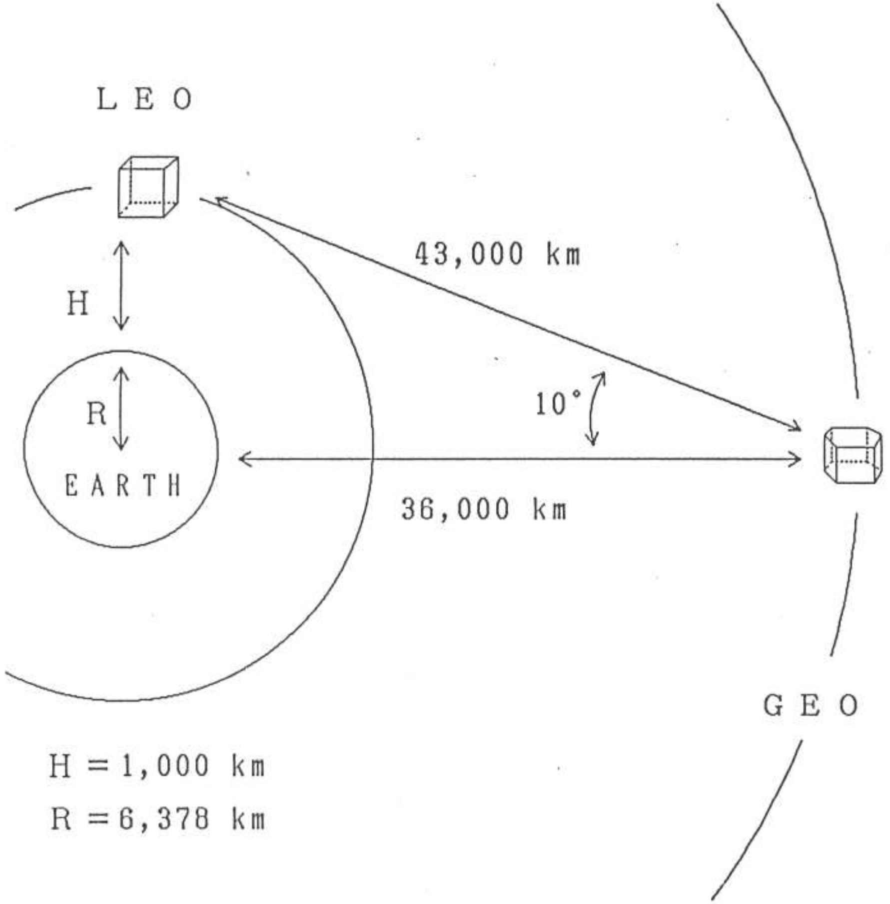
(2) To reduce RF interference

(3) To realize intersatellite data transmission of large capacity and high data rate

Target system parameters for ILC system

<table>
<tr><th>parameters</th><th>future system</th><th>experimental system</th></tr>
<tr><td>1. Link</td><td>GEO-GEO
GEO-LEO</td><td>GEO-LEO</td></tr>
<tr><td>2. Optics
Optical Antenna diameter</td><td>GEO;≦50cmφ
LEO;≧20cmφ</td><td>GEO;30cmφ
LEO;20～30cmφ</td></tr>
<tr><td>3. Communication
(1) wave length
(2) LD output power
(3) data rate</td><td>0.85, 1.30 or 1.55 μm band
100～200mW
≧1Gbps</td><td>0.85μm band
≧100mW
≧50Mbps</td></tr>
<tr><td>4. AT&P
(1) beacon wave length
(2) beacon output power
(3) acquisition range
(4) pointing accuracy
(5) point ahead drive angle
(6) point ahead pointing accuracy</td><td colspan="2">0.85μm band
≧100mW
[GEO-GEO] GEO X/Y;±50°
[GEO-LEO] GEO X/Y;±15°
LEO Az ;±180°
El ;±120°
≦±1μrad [with fluctuation of ±40μrad(sinewave, 1Hz)]
[GEO-GEO] ≧±45μrad
[GEO-LEO] ≧±75μrad
≦±1μrad</td></tr>
<tr><td>5. power consumption</td><td>TBD W</td><td>≦200W</td></tr>
<tr><td>6. weight</td><td>TBD kg</td><td>≦100kg</td></tr>
</table>

Concept of ILC between GEO and LEO



Target parameter of AT&P subsystem

AQUISITION & TRACKING	
acquisition range	
GEO	± 15°(X/Y)
LEO	± 180°(Az) ± 120°(El)
pointing accuracy	≦ ± 1 μrad
POINT AHEAD	
angle range	± 75 μrad
pointing accuracy	≦ ± 1 μrad
COMMUNICATION BEAM	
pointing error	≦ ± 3 μrad

Trial fabrication of AT&P subsystems

AT&P (Acquisition, Tracking & Pointing) subsystem is a critical technology for establishing and maintaining ILC links.

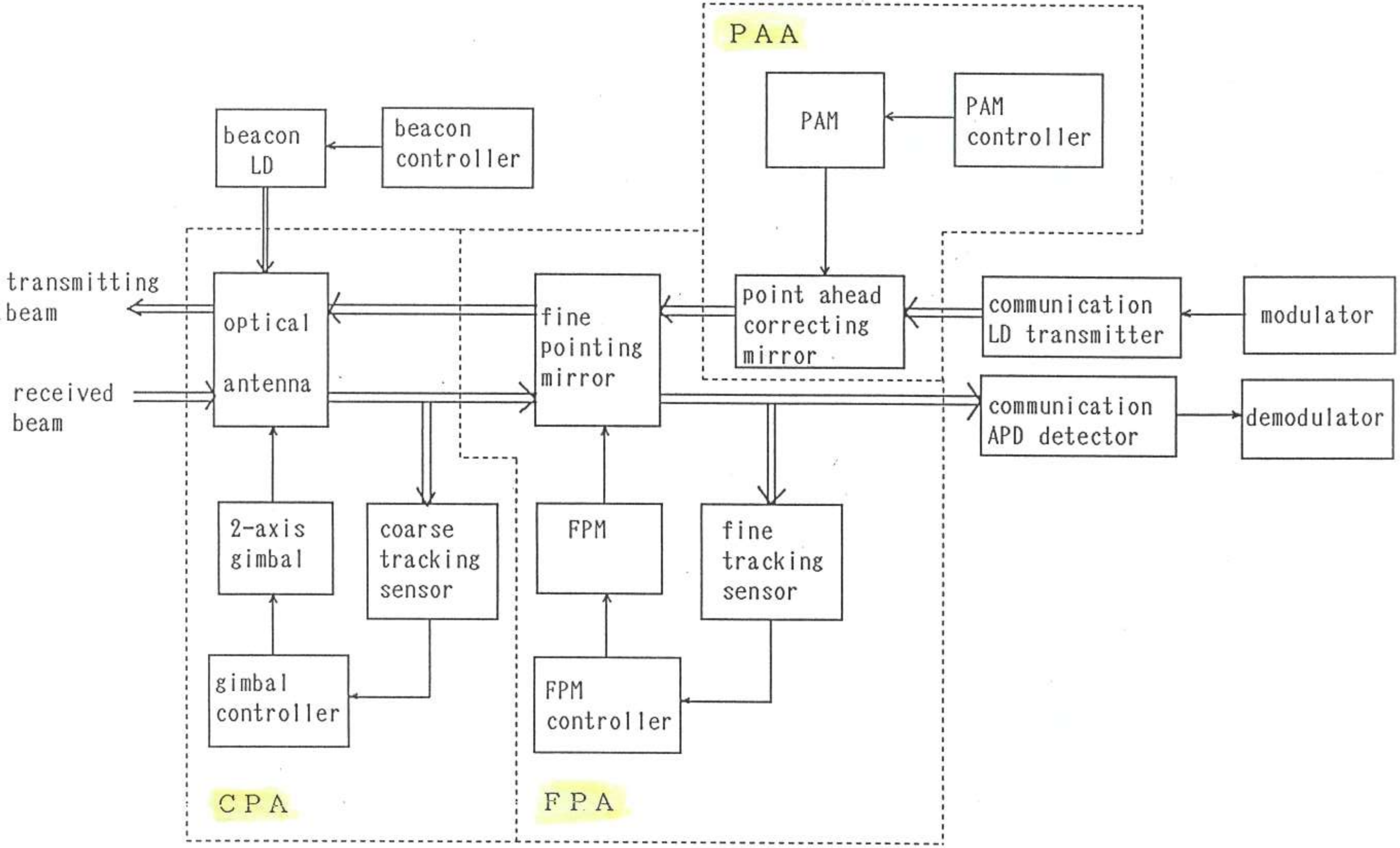
Acquisition and Tracking between GEO and LEO		
	GEO	LEO
range	±15 deg (X/Y)	±180 deg (Az) ±120 deg (El)
accuracy	≦±1 μrad	

⇨ very wide range acquisition

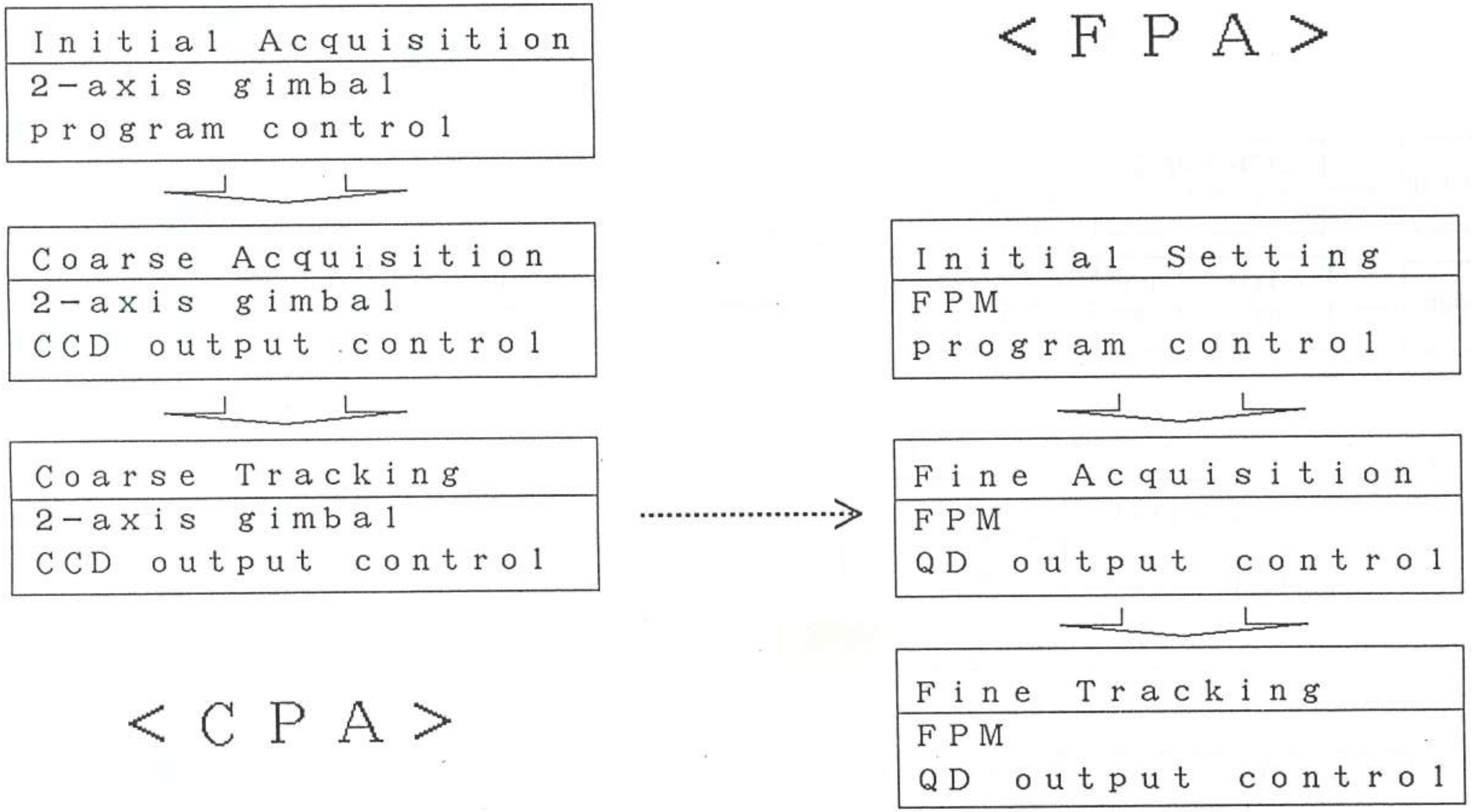
⇨ very high accuracy tracking

- Confirmation of function, principle and configuration of AT&P subsystem by trial fabrication of AT&P subsystem elements

Conceptual block diagram of ILC system



Sequence of Acquisition and Tracking in CPA and FPA



Initial Acquisition
2-axis gimbal
program control

Coarse Acquisition
2-axis gimbal
CCD output control

Coarse Tracking
2-axis gimbal
CCD output control

<CPA>

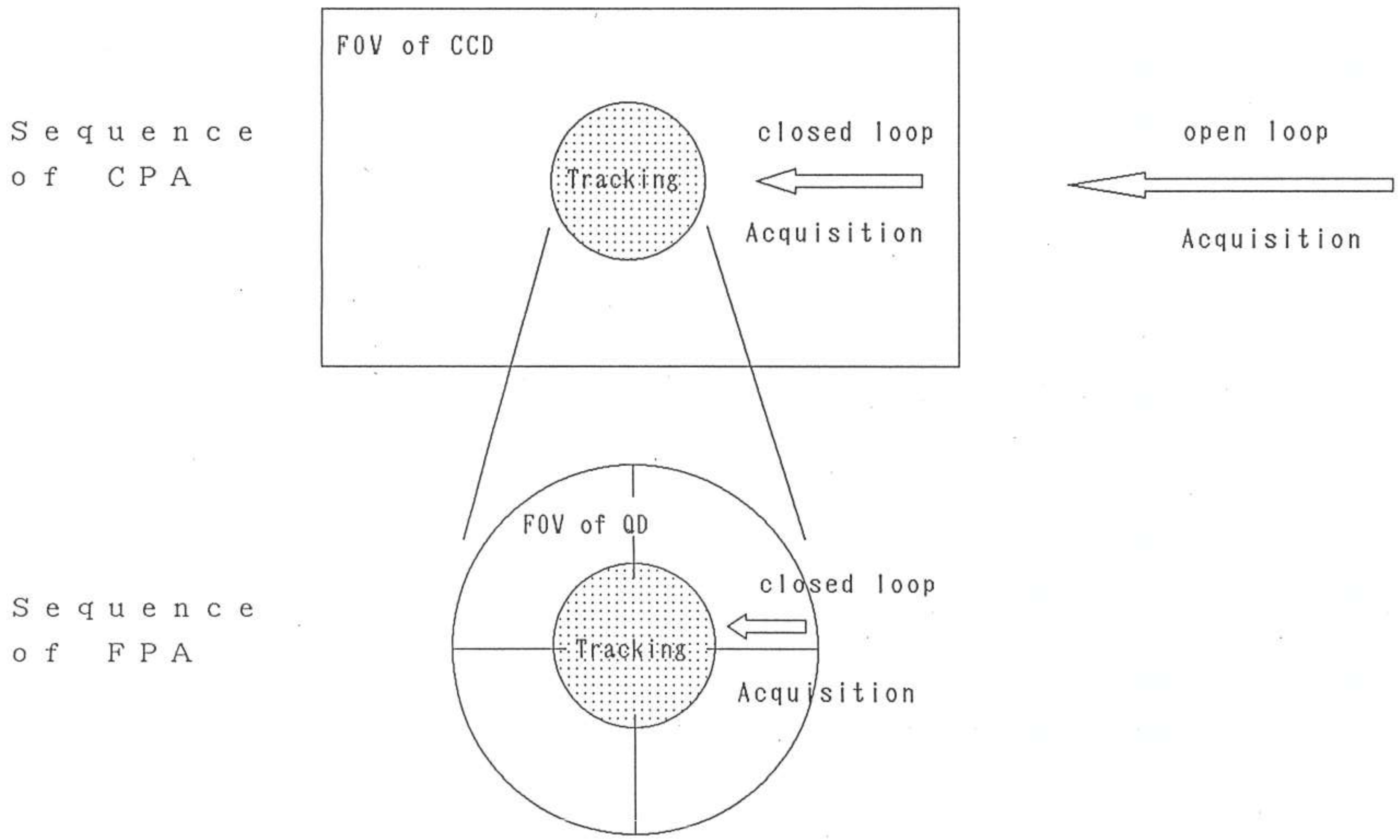
<FPA>

Initial Setting
FPM
program control

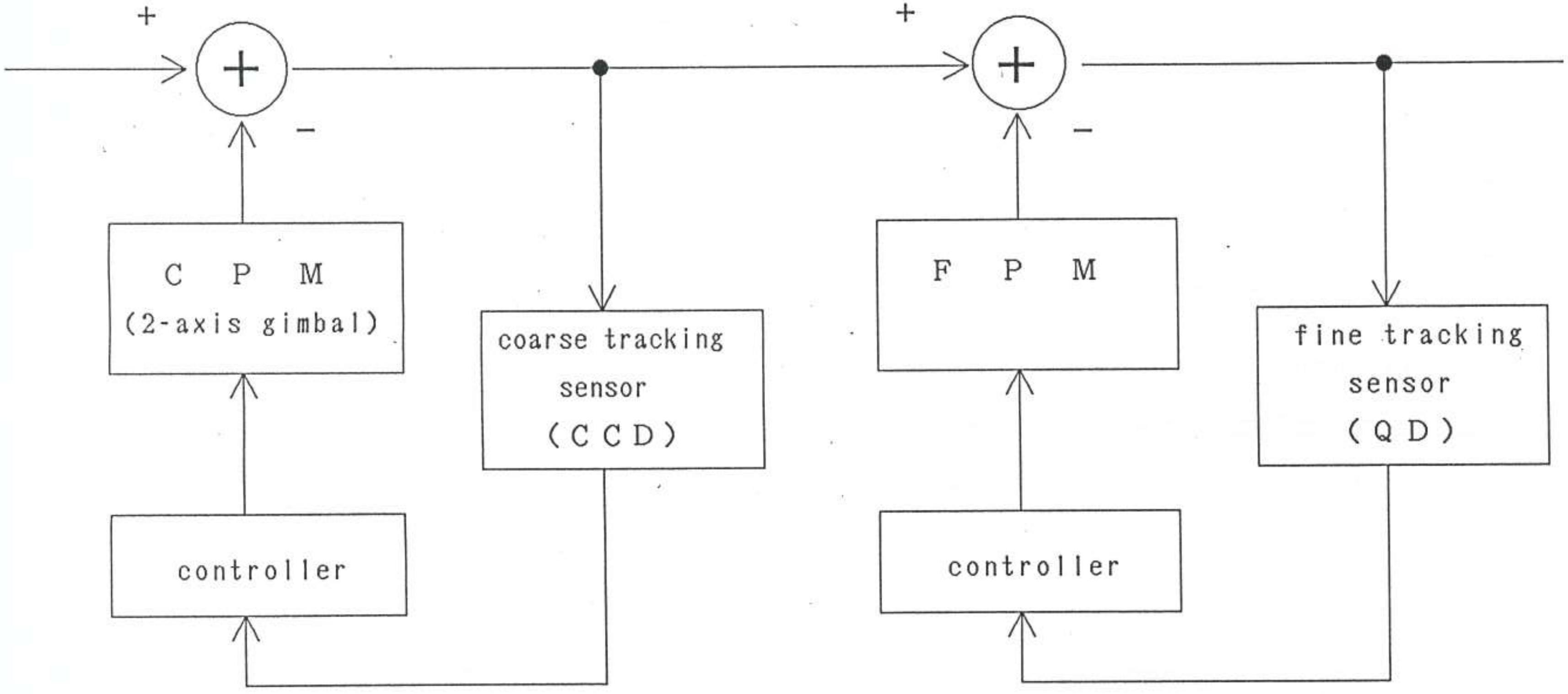
Fine Acquisition
FPM
QD output control

Fine Tracking
FPM
QD output control

Acquisition and Tracking Sequence of CPA to FPA



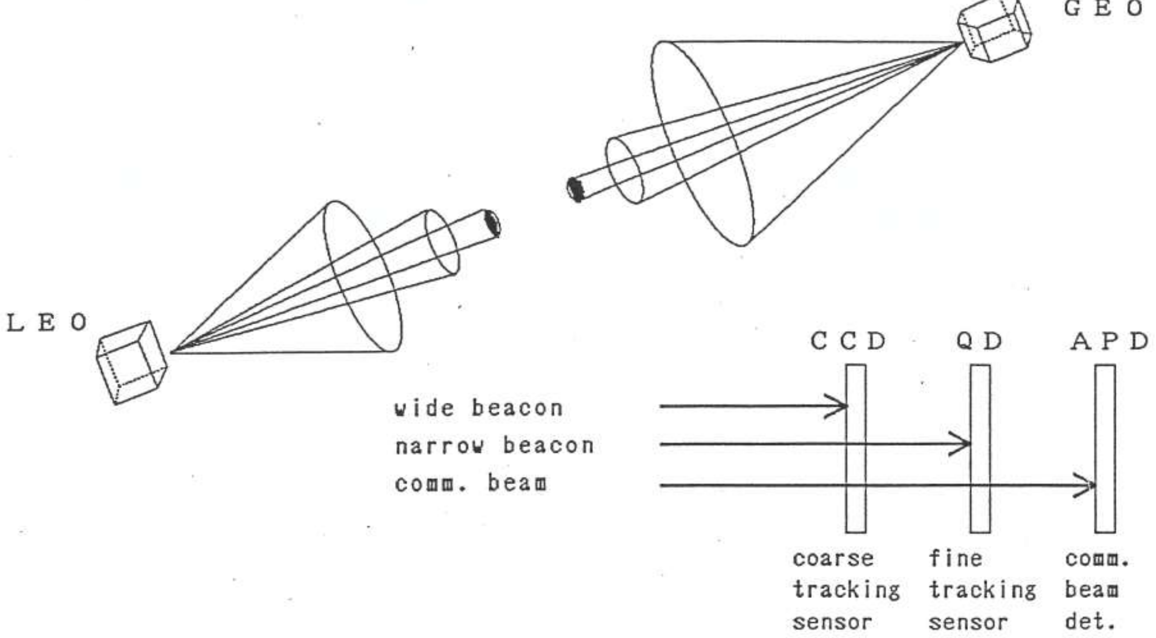
Suppression of disturbance by AT&P subsystem



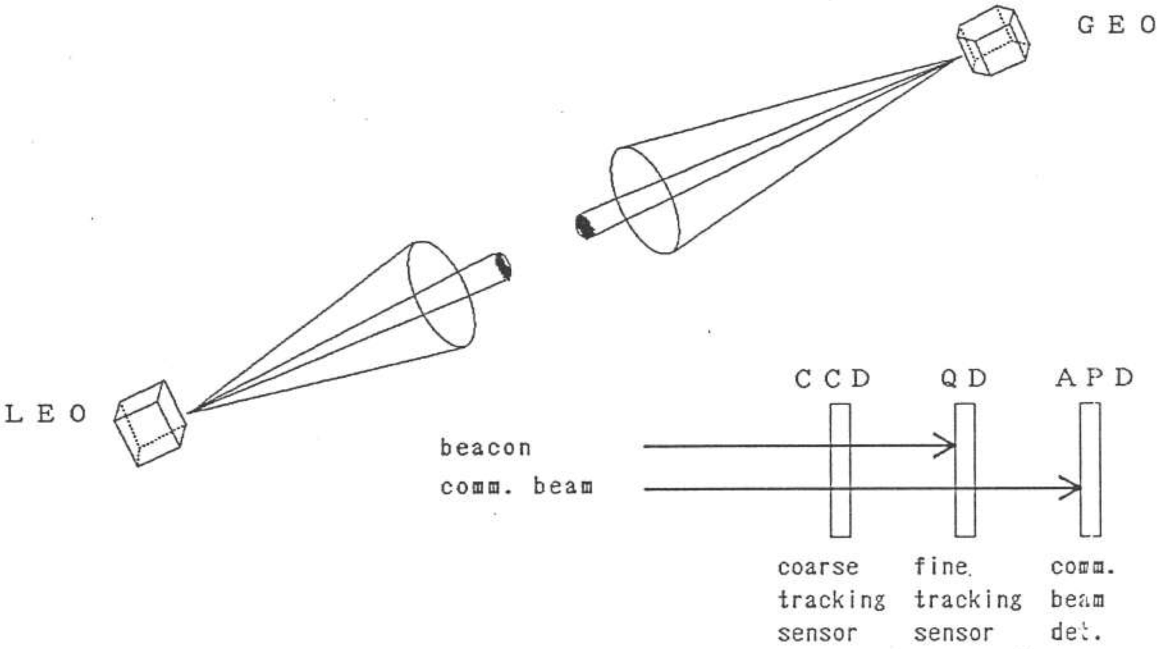
- Suppression of low frequency components (ex. ～1Hz)
- Suppression of high frequency components (ex. 1Hz～200Hz)

Example of transmitting beams for ILC

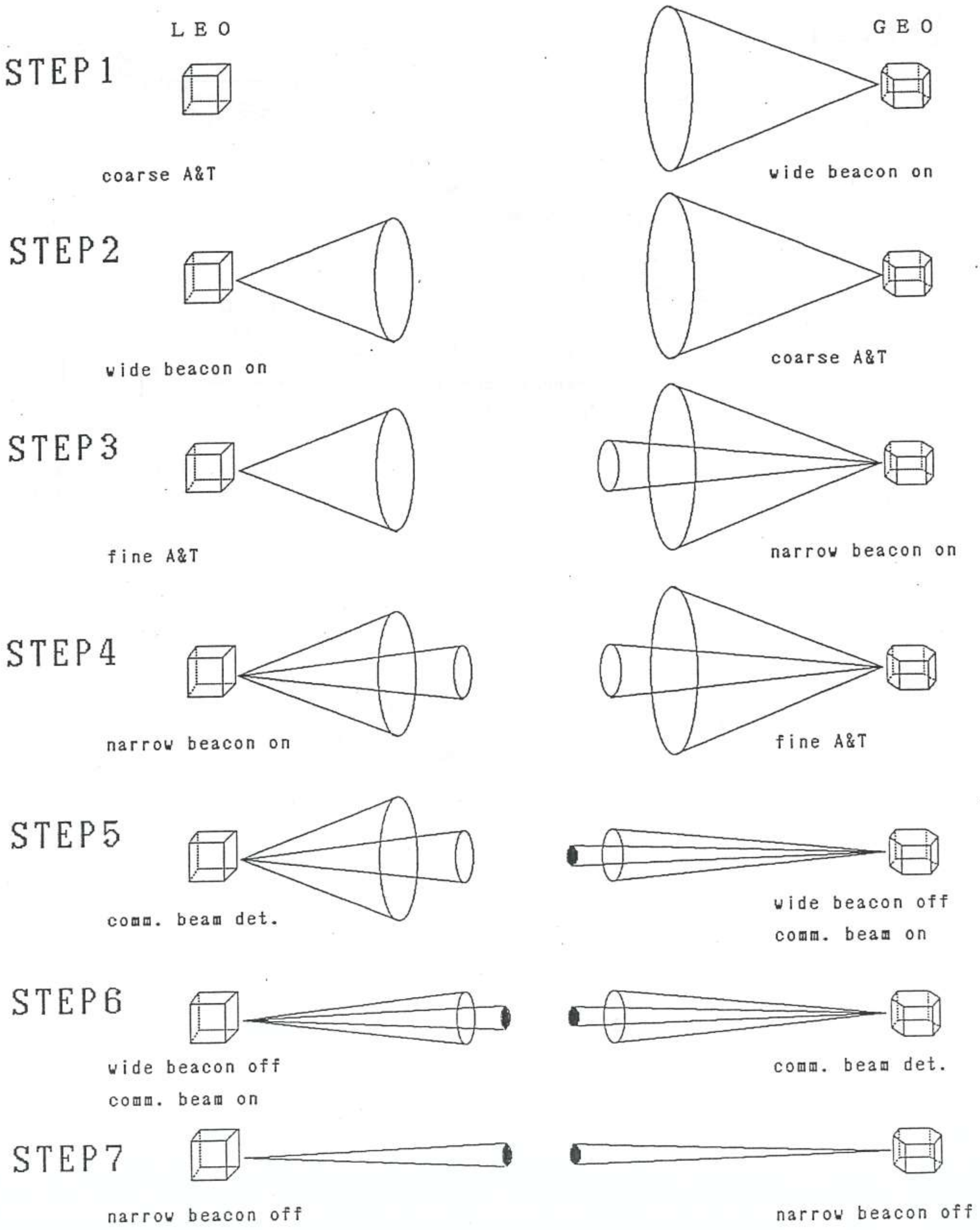
[Ex.1]



[Ex.2]



Example of AT&P sequence of GEO to LEO



Target specifications for trial model

items	function & performance
1. Coarse acquisition control	
(1) H/W	2-axis gimbal plate
(2) driver	TBD
(3) sensor	CCD(charge coupled device)
(4) sensor FOV	TBD
(5) acquisition range	±180° (1-axis)
(6) pointing accuracy	<FOV of fine acquisition sensor
2. Fine acquisiton control	
(1) H/W	mirror deflector
(2) sensor	QD(quadrant detector)
(3) sensor FOV	TBD
(4) pointing accuracy	≦±1μrad
3. Tracking control	
(1) H/W	2-axis gimbal plate and mirror deflector
(2) ponting accuracy	≦±1μrad
(3) control frequency characteristics	TBD
4. Point ahead control	
(1) H/W	mirror deflector
(2) driving angle range	≧±75μrad
(3) pointing accuracy	≦±1μrad
(4) control frequency characteristics	TBD

① beacon
0,1~0,4°
② beam divergence.
〃 / 40~400
μrad.

③ Comm.
<10 μrad.

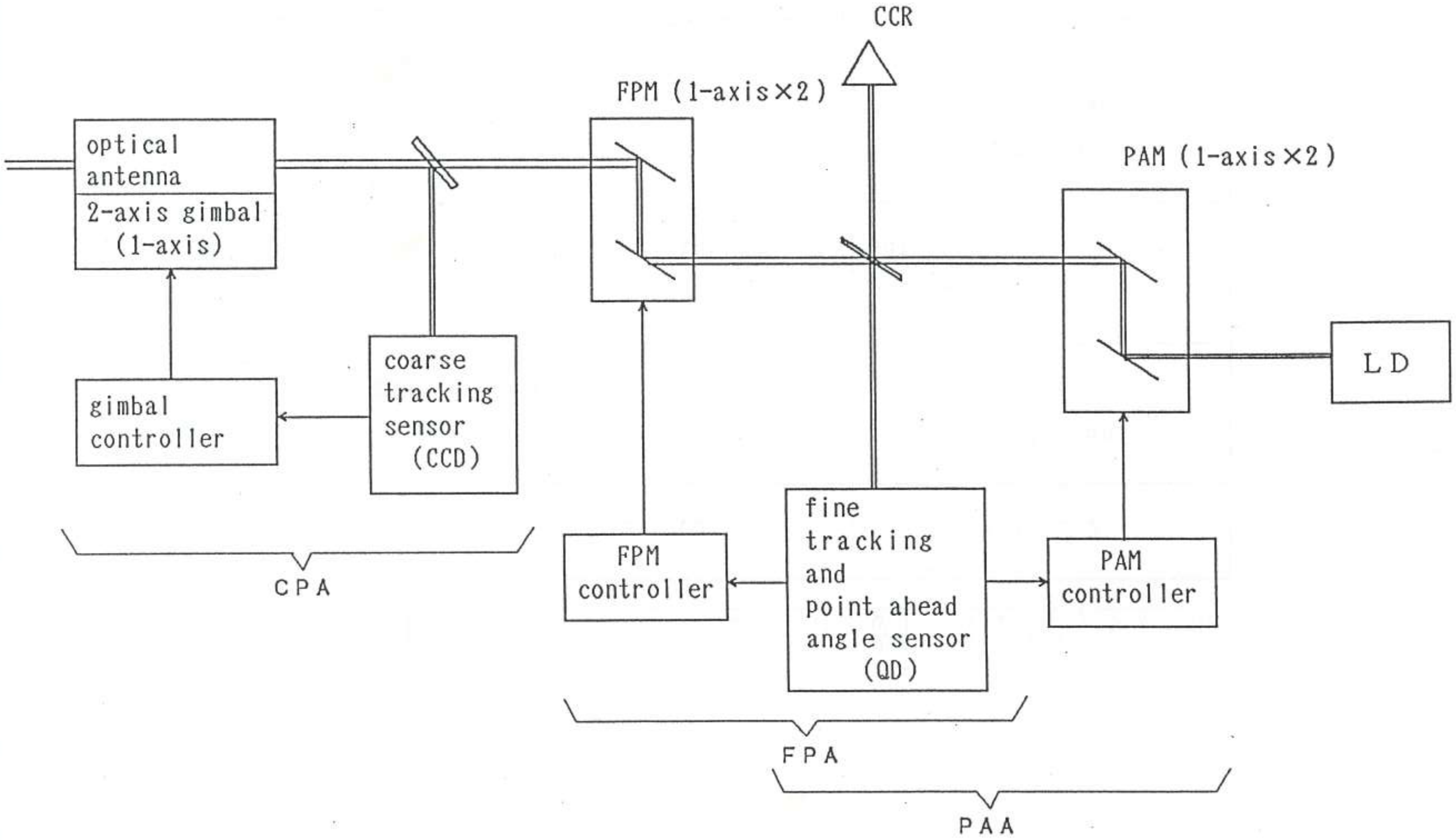
Trial fabrications for AT&P subsystem at NASDA

items of trial fabrication and evaluation	period
• FPM(Fine Pointing Mechanism) ○ Evaluation of FPM	1987.09～1988.09
<CPA> • 2-axis gimbal and controller • coarse acquisition and tracking sensor(CCD), and signal processor <FPA> • FPM controller • fine acquisition and tracking sensor(QD), and signal processor <OPTICS> • trial optics for conducting beam ○ Evaluation of combination of CPA and FPA	1988.12～1989.12
<PAA> • PAM(Point Ahead Mechanism) and controller ○ Evaluation of AT&P subsystem	1990.02～1991.03

Driving mechanism for AT&P subsystem

	method-A	method-B
2-axis gimbal drive mechanism for CPA	direct drive motor	stepping motor and harmonic drive
fine pointing mirror deflector for FPA	multi-layered piezo-electric actuator	moving coil type actuator
point ahead correcting mirror deflector for PAA	multi-layered piezo-electric actuator	torsion bimorph type piezo-electric actuator

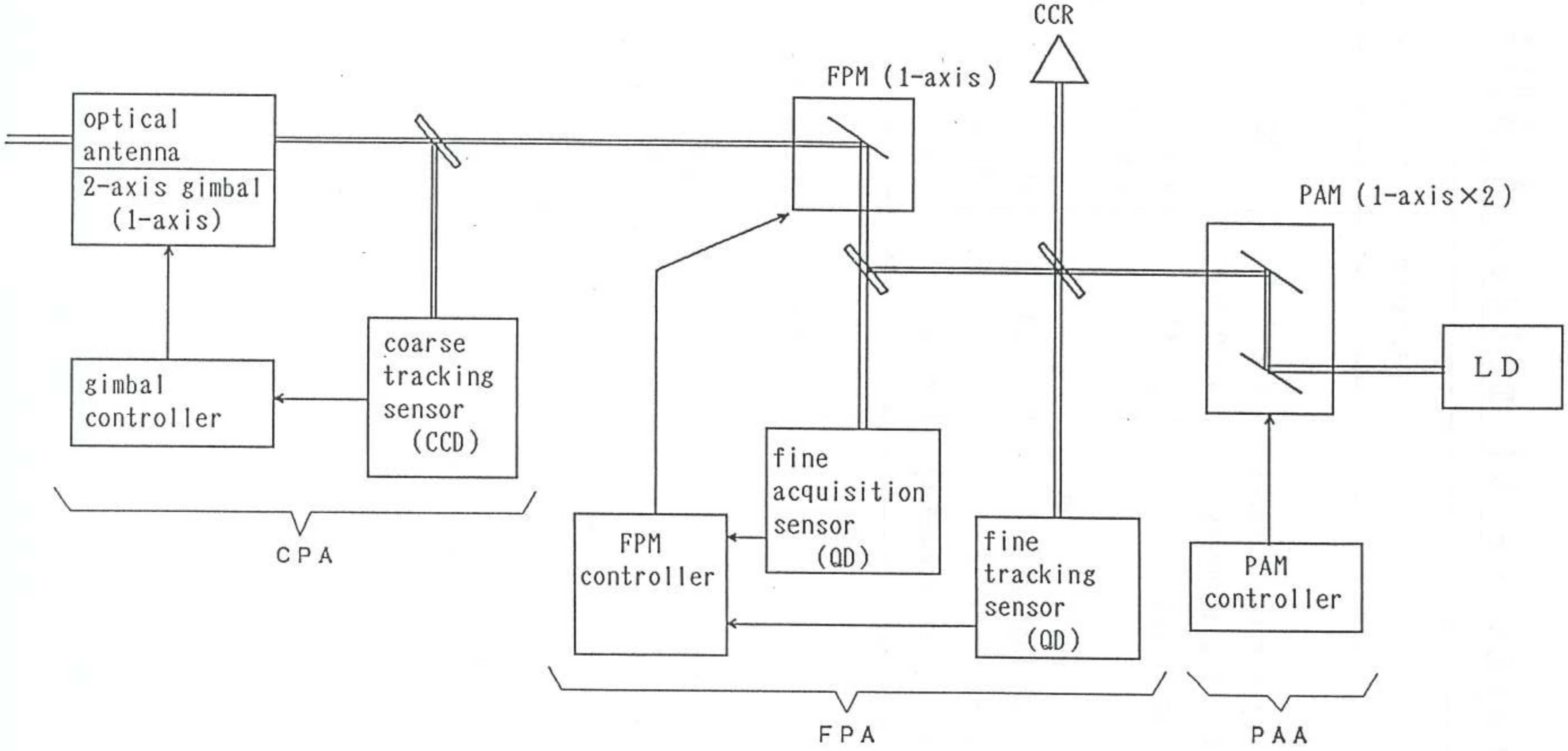
Block diagram of the method-A trial AT&P model



Performance of method-A AT&P subsystem

	targets	test results	notes
1. CPA			
(1) driving angle range	±180°	±180°	1-axis
(2) driving accuracy	≦±0.002°	±0.004°	
(3) sensor FOV	≧0.4°	H:0.56° V:0.42°	
(4) frequency response			
open loop gain	>30dB	29dB	at 0.1Hz
phase margine	>30°	70deg	
crossover frequency	>1Hz	1Hz	
2. FPA			
(1) driving angle range	>±6mrad	±7.2mrad	deflection angle
(2) pointing accuracy	≦±1μrad	≦±0.75μrad	
(3) sensor FOV	≧0.02°	0.049°	f=120mm
(4) frequency response			
open loop gain	>32dB	34.6dB	at 1Hz
phase margine	>30°	34°	
crossover frequency	>50Hz	57Hz	
3. PAA			
(1) driving angle range	>±75μrad	under evaluation	
(2) ponting accuracy	≦±1μrad		
(3) frequency response			
open loop gain	≧45dB		at 0.01Hz
phase margine	≧30deg		
crossover frequency	≧1Hz		

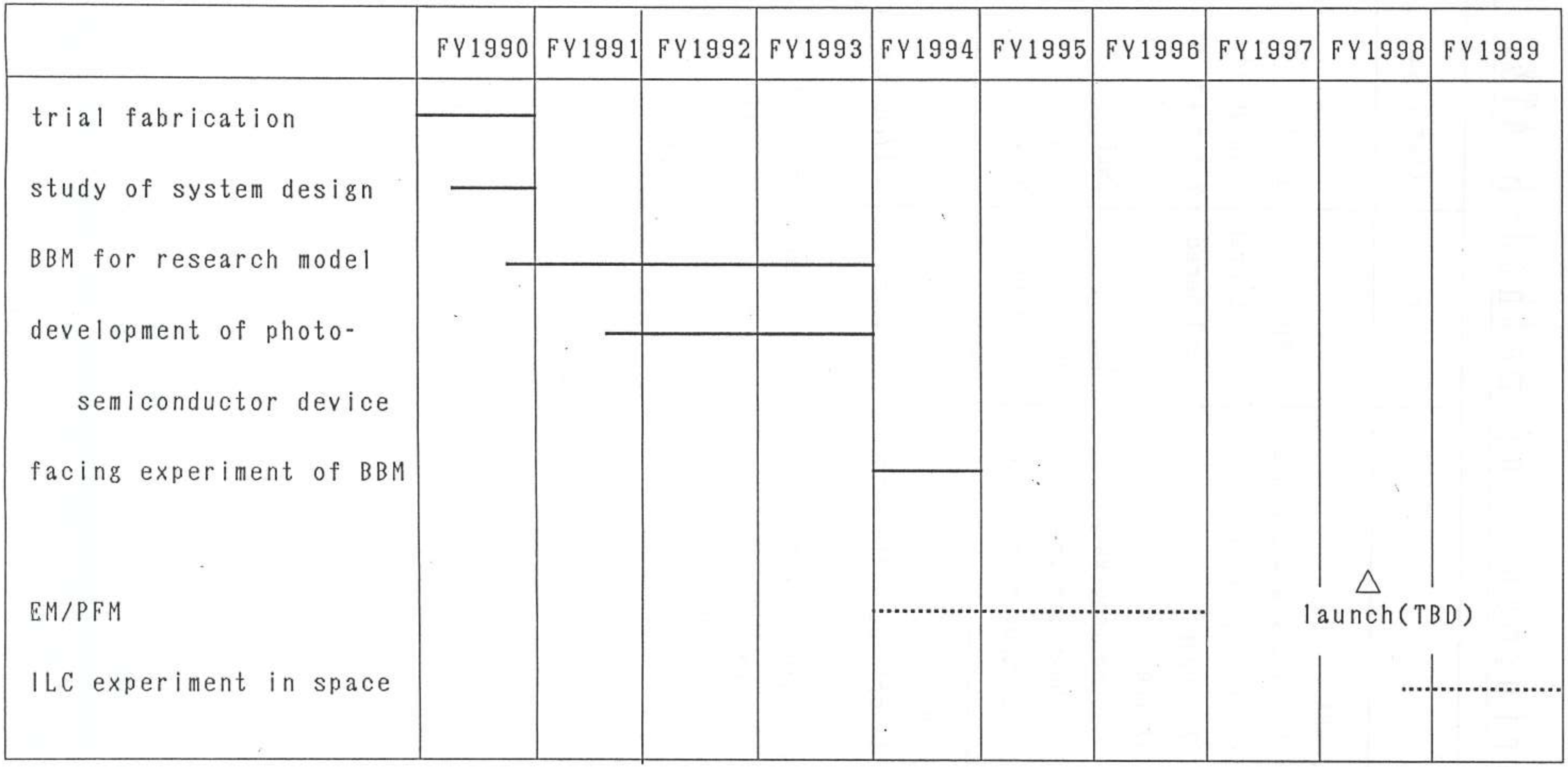
Block diagram of the method-B trial AT&P model



Performance of method-B AT&P subsystem

	targets	test results	notes
1. CPA			
(1) driving angle range	±180°	±180°	1-axis
(2) driving accuracy	≦±240μrad	±506μrad	
(3) sensor FOV	≧±3.8mrad	7.15mrad	
(4) frequency response			
open loop gain	41dB	39dB	at 0.001Hz
phase margine	40～60°	51°	
crossover frequency	0.1±TBDHz	0.1Hz	
2. FPA			
(1) driving angle range	±7.2mrad	±17.5mrad	deflection angle
(2) pointing accuracy	≦±1μrad	±0.7μrad	
(3) sensor FOV	485μrad	870μrad	
(4) frequency response			
open loop gain	27dB	23dB	at 20Hz
phase margine	40° ～60°	60°	
crossover frequency	200Hz	closed loop band width 200Hz	
3. PAA			
(1) driving angle range	>±75μrad	under evaluation	
(2) ponting accuracy	≦±1μrad		
(3) frequency response			open loop control
open loop gain	TBD		
phase margine	TBD		
crossover frequency	TBD		

Schedule for ILC Research & Development



Session 2

Coherent Technologies for Optical Space Communications

2-1

Intersatellite optical heterodyne communications system

Vincent W. S. Chan

MIT Lincoln Lab.

IWOSC '90

December 6 and 7, 1990, ATR, Kyoto

Intersatellite Optical Heterodyne Communication System

Vincent W. S. Chan
Massachusetts Institute of Technology, Lincoln Laboratory
Lexington, Massachusetts 02173-9108

Summary

High-capacity intersatellite communication crosslinks will allow more efficient and reliable operation of military and commercial satellite systems. High-speed optical crosslinks can serve as a key building element of an interconnected space-based communication system for military applications. A network such as this would provide immediate communication among satellites, eliminating the need for ground-based relay stations and expensive worldwide ground tracking networks, which would greatly improve the efficacy and reduce the vulnerability of existing satellite systems. Crosslinks can also provide connectivity for commercial global satellite communication systems and for deep-space applications. Optical heterodyne communication systems using semiconductor lasers offer small-aperture, modest-weight, low-power, point-to-point crosslink packages, characteristics that are suitable for the envisioned applications. System research and development performed at Lincoln Laboratory permits the implementation of an efficient optical crosslink based on readily available, state-of-the-art devices and technology.

The added sensitivities of heterodyne systems over direct detection systems offer 15-dB higher efficiency in the use of signal power. This system uses a laser of modest power (30 mW) and small apertures (20 cm). Our research and development program has addressed critical technology and system issues toward the realization of such an optical communication system. It is now possible to assemble a system using current technologies. The characteristics of such a system will be extremely competitive with 60 GHz crosslink technology, especially in the high-data-rate region. Ultimately, cost will also be a major consideration. This system is based upon commercially available devices, which, coupled with the ongoing development of these devices, should make this system cost-competitive as well as technologically attractive.

Information on a system to be described is based on a space-flight experimental design performed at Lincoln Laboratory. The numbers and characteristics set forth here are the result of a substantial development effort and are detailed by test data or estimates based on detailed designs. We are building a system with the described characteristics for space qualifications in the early 1990's.

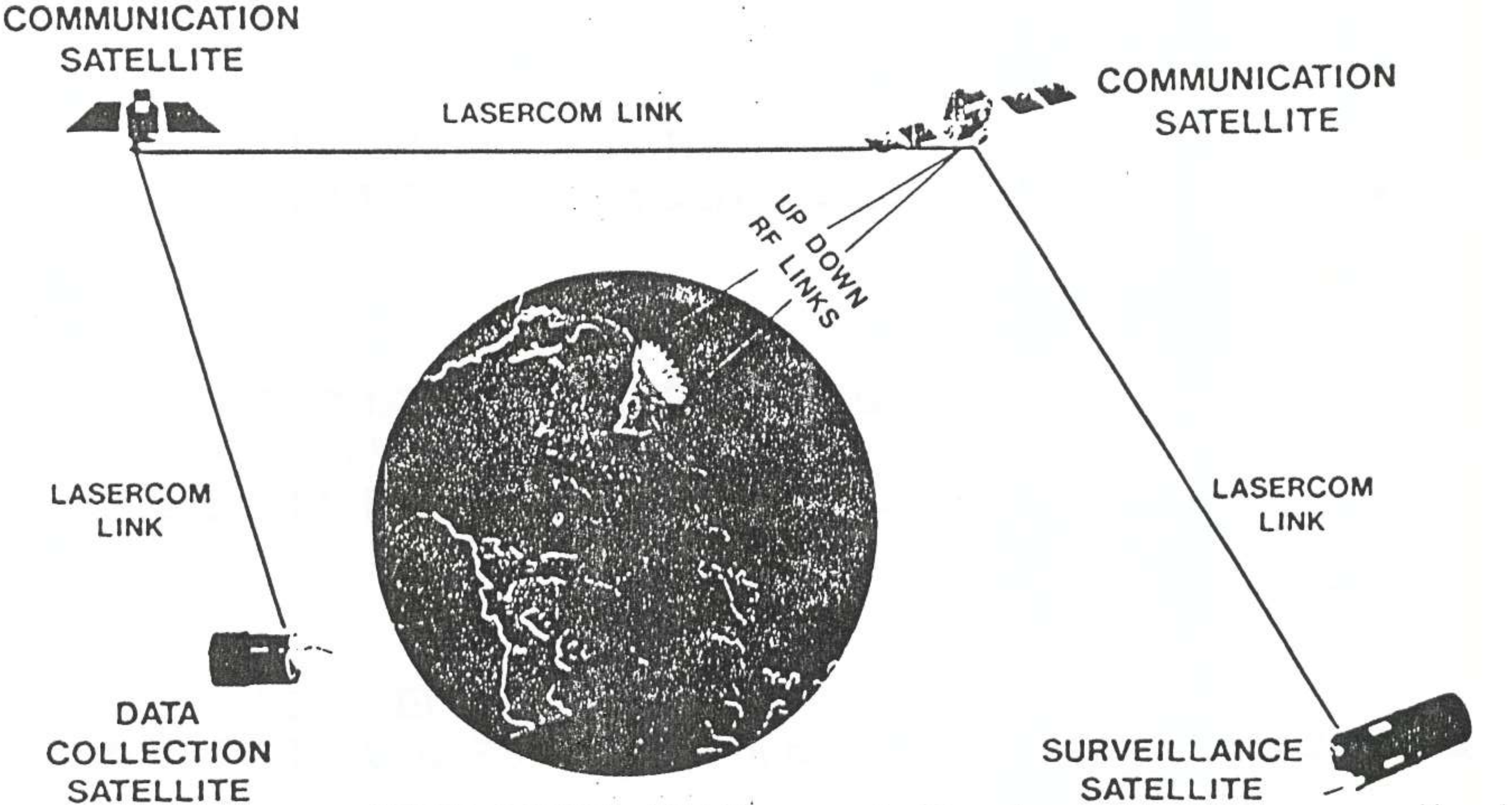
VINCENT W. S. CHAN

Vincent W. S. Chan was born in Hong Kong on November 5, 1948. He received his BS, MS, EE, and PhD degrees in electrical engineering from MIT, Cambridge in 1971, 1971, 1972 and 1974, respectively, in the area of communication. From 1974 to 1977, he was an assistant professor with the School of Electrical Engineering at Cornell University, teaching and conducting fundamental research in communication and optics. He joined Lincoln Laboratory in 1977 as a staff member of the Satellite Communication System Engineering Group. In January 1981, he became the Assistant Leader of the Communication Technology Group starting a research and development program on optical space communication based on semiconductor lasers and coherent detection techniques. In July 1983, he formed and became leader of the Optical Communication Technology Group and leader of the LITE Project Office. He is currently the Associate Head of the Communication Division.

His research interests are in optical communication, space communication and networks. Of particular interest is the interplay between system and technology and how to create and demonstrate sensible communication systems.

He was the guest editor of a special joint issue of the Journal of Lightweight Technology and Selected Area in Communications on Coherent Communications.

LASER COMMUNICATIONS TECHNOLOGY PROGRAM



- HIGH SPEED (1 Mbps - 5 Gbps)
- MODEST SIZE, WEIGHT AND POWER PACKAGE

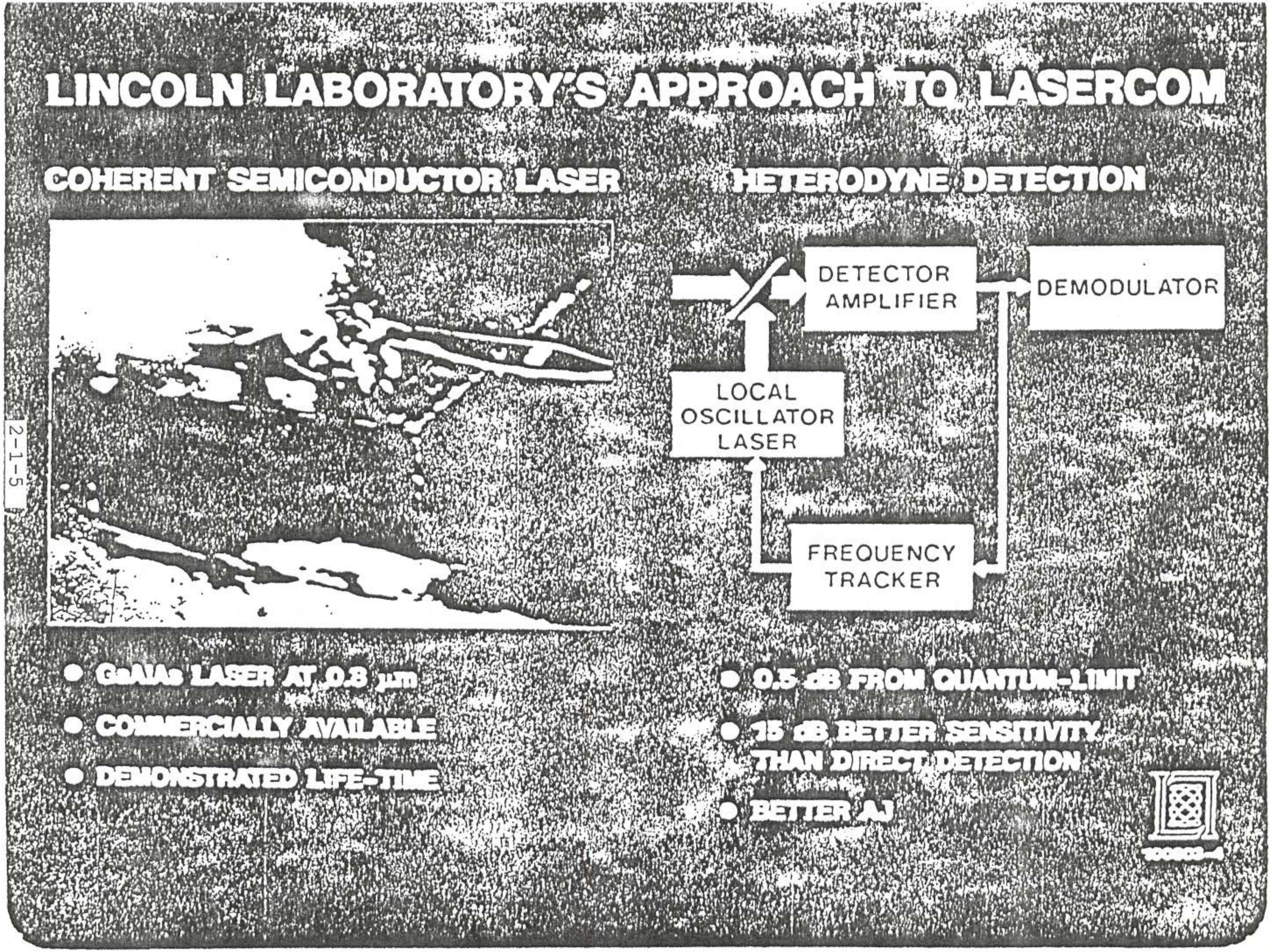
MAJOR CHALLENGES OF SPACE LASERCOM DESIGN

- AVAILABILITY OF SPACE-QUALIFIED/QUALIFIABLE COMPONENTS AND SUBSYSTEMS

- NEW ENGINEERING DISCIPLINE REQUIRED FOR PRECISE MECHANICAL/THERMAL/OPTICAL DESIGN/FABRICATION/INTEGRATION/TESTING

- SPATIAL ACQUISITION/TRACKING IN PRESENCE OF SIGNIFICANT SPACECRAFT MICROMOTIONS

- PREDICTABLE PROGRAM COSTS AND SCHEDULES



LINCOLN LABORATORY'S APPROACH TO LASERCOM

COHERENT SEMICONDUCTOR LASER

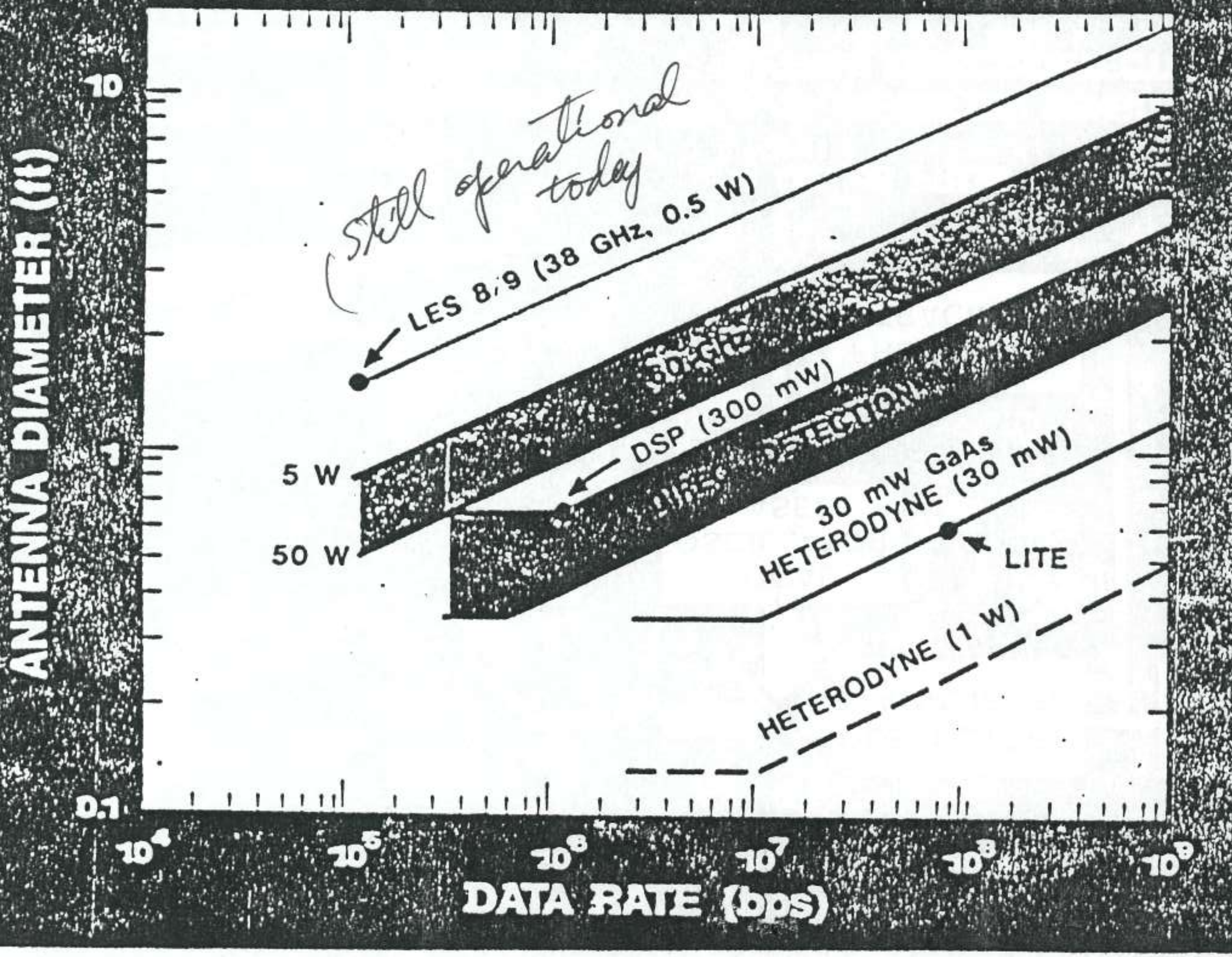
- GaAlAs LASER AT 0.8 μm
- COMMERCIALLY AVAILABLE
- DEMONSTRATED LIFE-TIME

HETERODYNE DETECTION

- 0.5 dB FROM QUANTUM-LIMIT
- 15 dB BETTER SENSITIVITY THAN DIRECT DETECTION
- BETTER AJ

COMPARISON OF CROSSLINK SYSTEMS

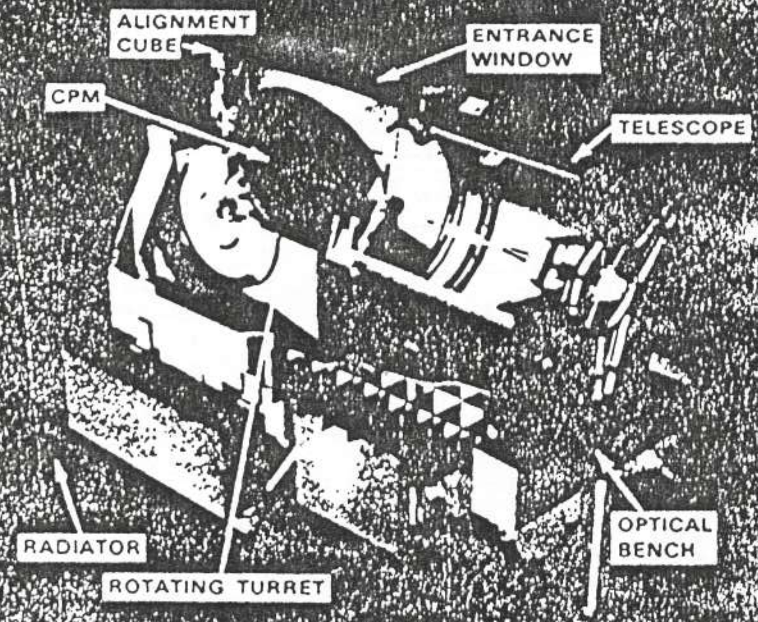
(1 × Sync Distance)

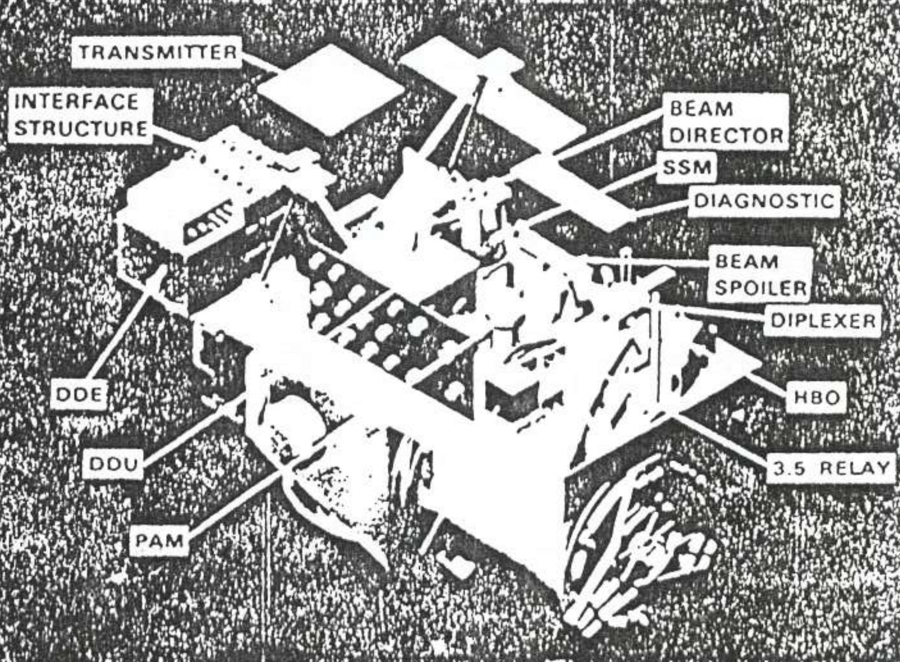


(Still operational today

100928-1

LASER INTERSATELLITE TRANSMISSION EXPERIMENT OPTICAL MODULE



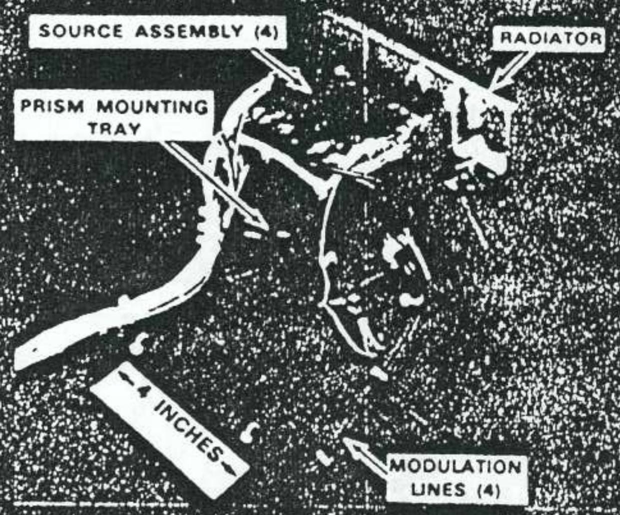


- HETERODYNE FSK COMMUNICATIONS
- 220 Mbps OVER 22000 MILES
- 30 mW SEMICONDUCTOR LASER DIODE
- 20 cm TELESCOPE

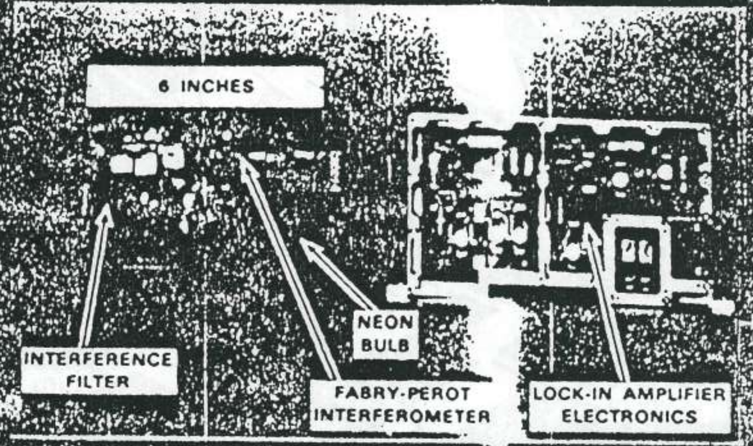
1461843

LASERCOM FLIGHT SUBSYSTEMS

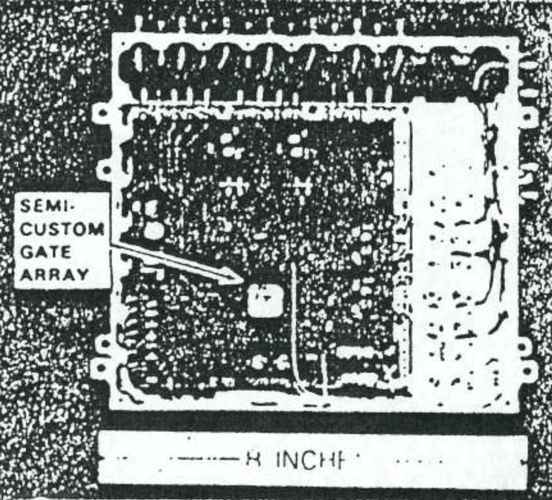
30 mW LASER TRANSMITTER



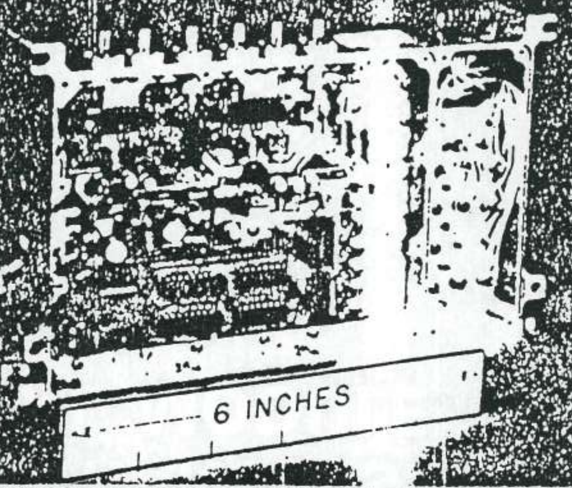
LASER DIAGNOSTICS MODULE



220 Mbps DATA FORMATTER



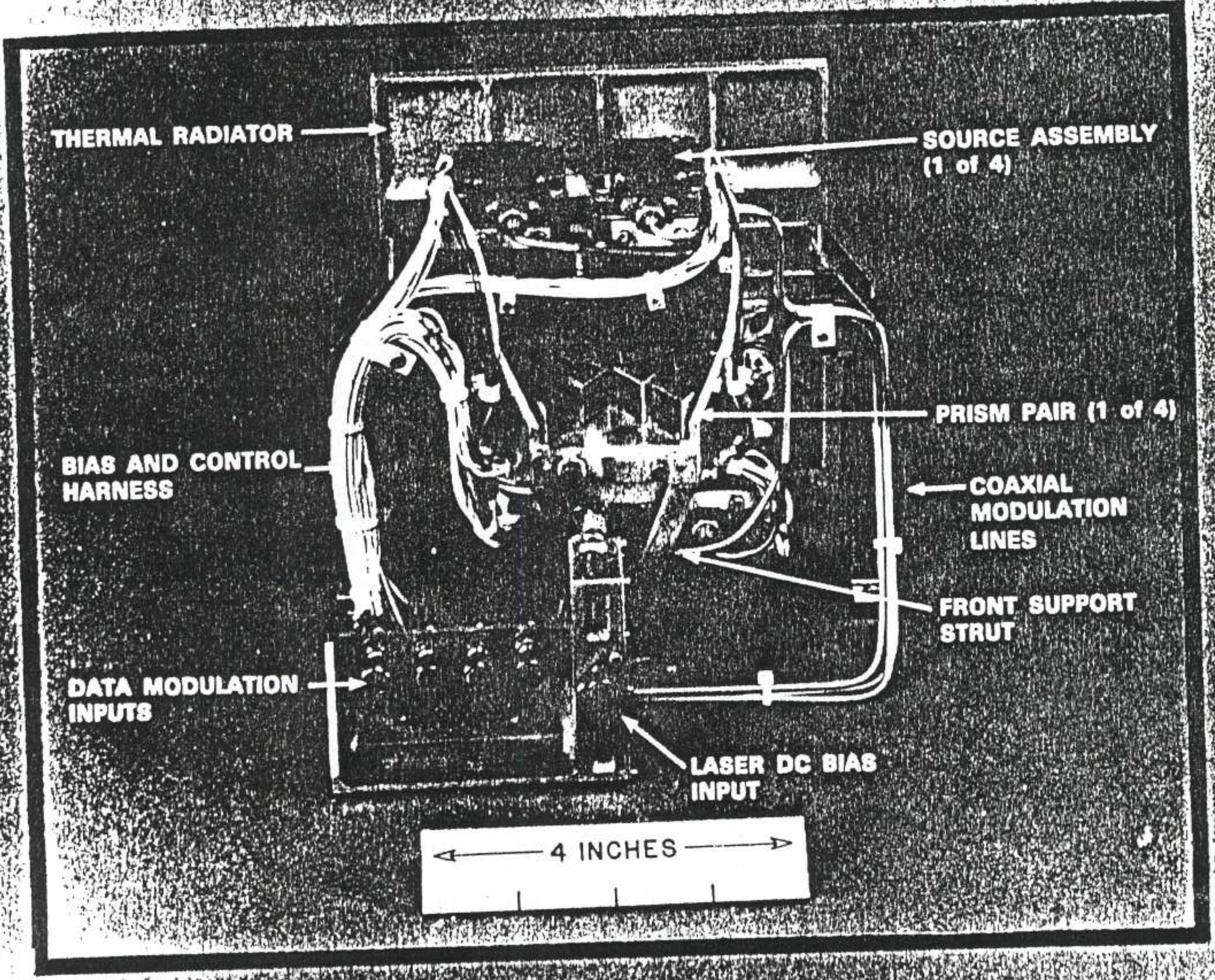
LASER FSK MODULATOR

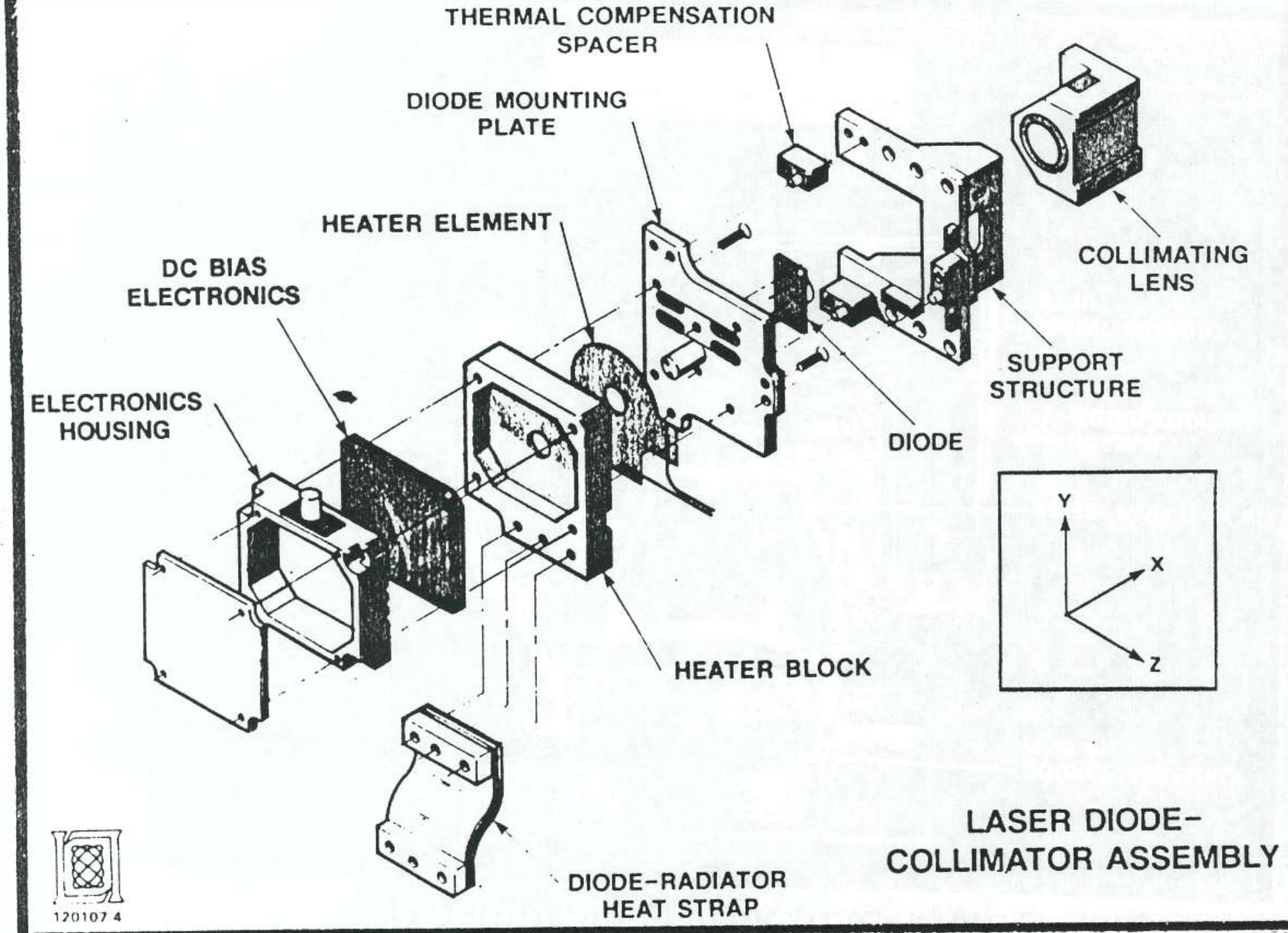


122832-1

LITE TRANSMITTER

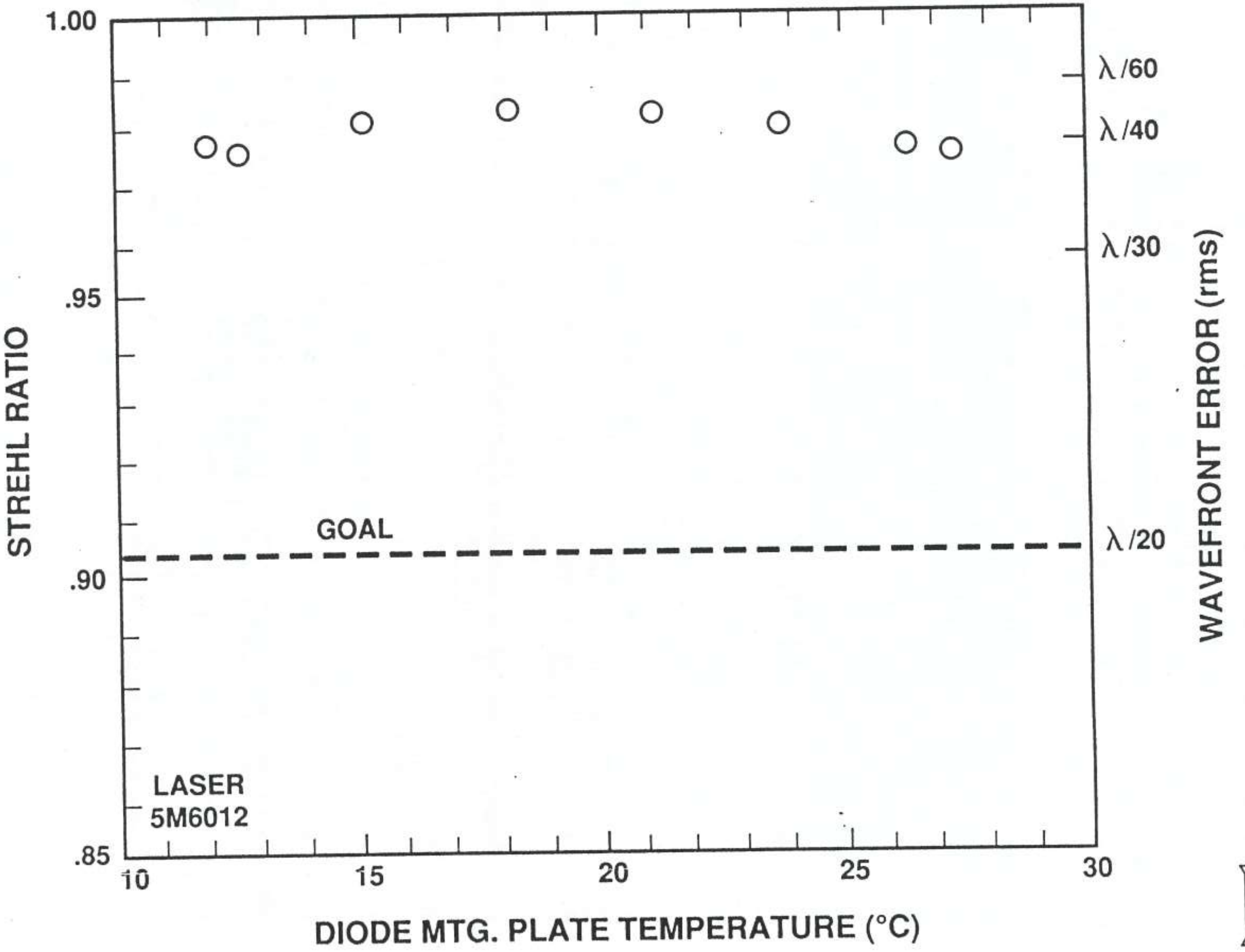
WEIGHT = 1.96 kg, POWER < 5 W





LASER DIODE-COLLIMATOR ASSEMBLY

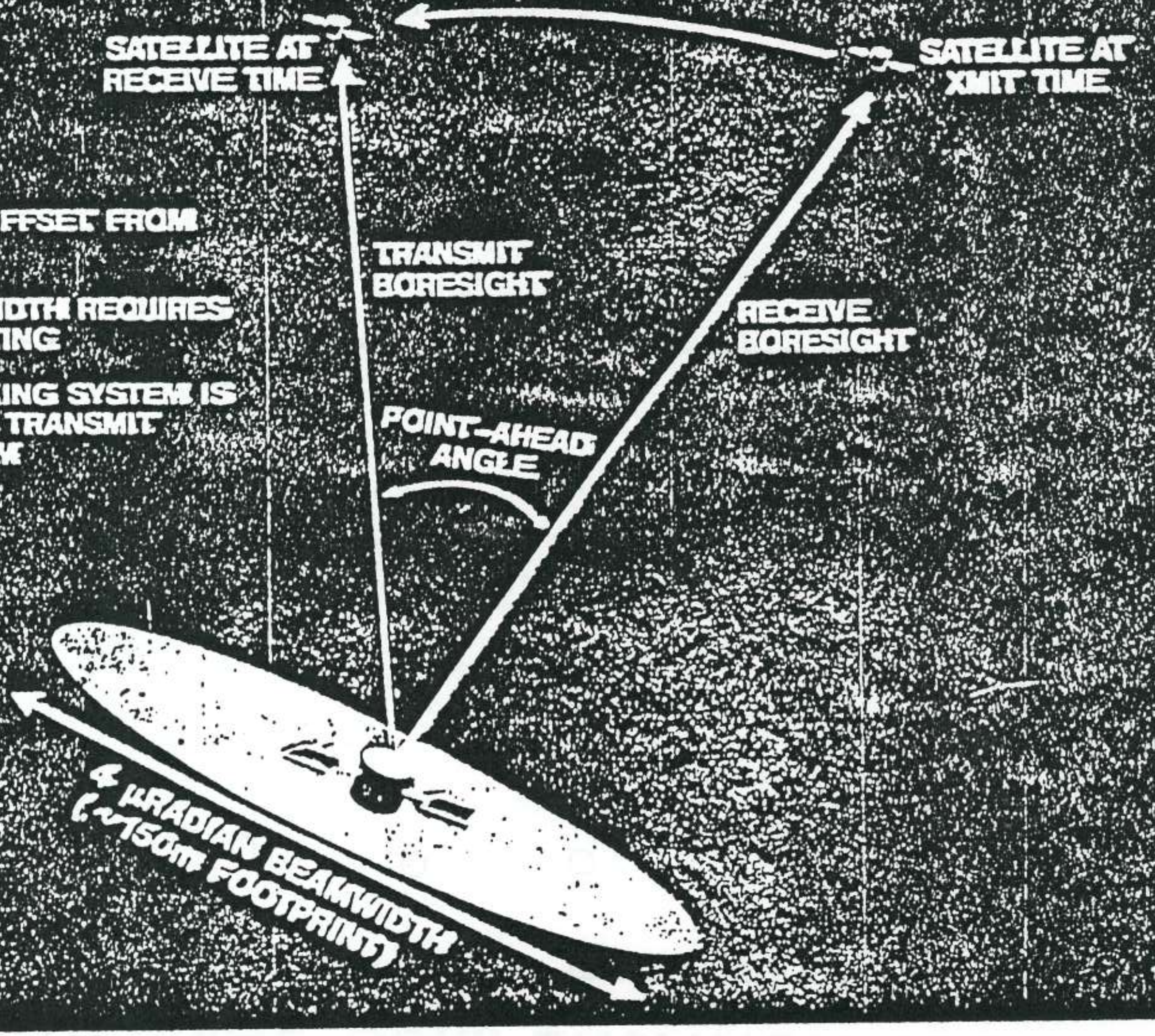
SOURCE ASSEMBLY THERMAL COMPENSATION TEST



120074-2

POINT-AHEAD AND TRACKING REQUIREMENTS

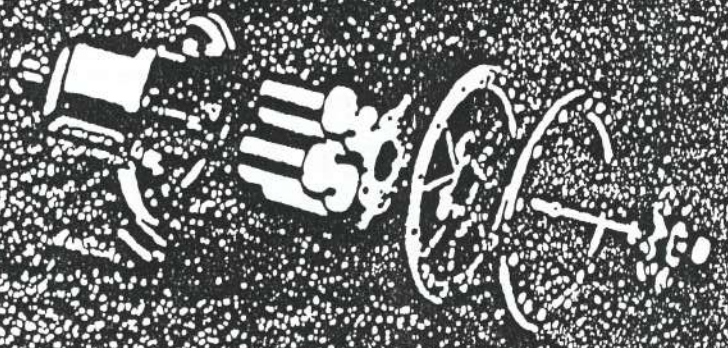
- TRANSMIT LOS OFFSET FROM RECEIVE LOS
- NARROW BEAMWIDTH REQUIRES ACCURATE POINTING
- RECEIVER TRACKING SYSTEM IS REFERENCE FOR TRANSMIT POINTING SYSTEM



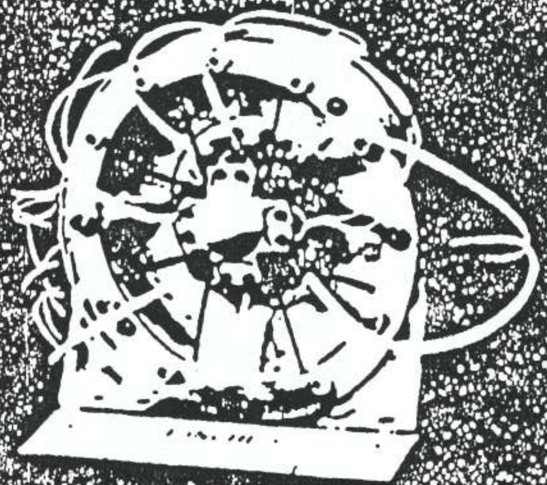
102329-1

HIGH BANDWIDTH STEERING MECHANISM

EXPLODED VIEW

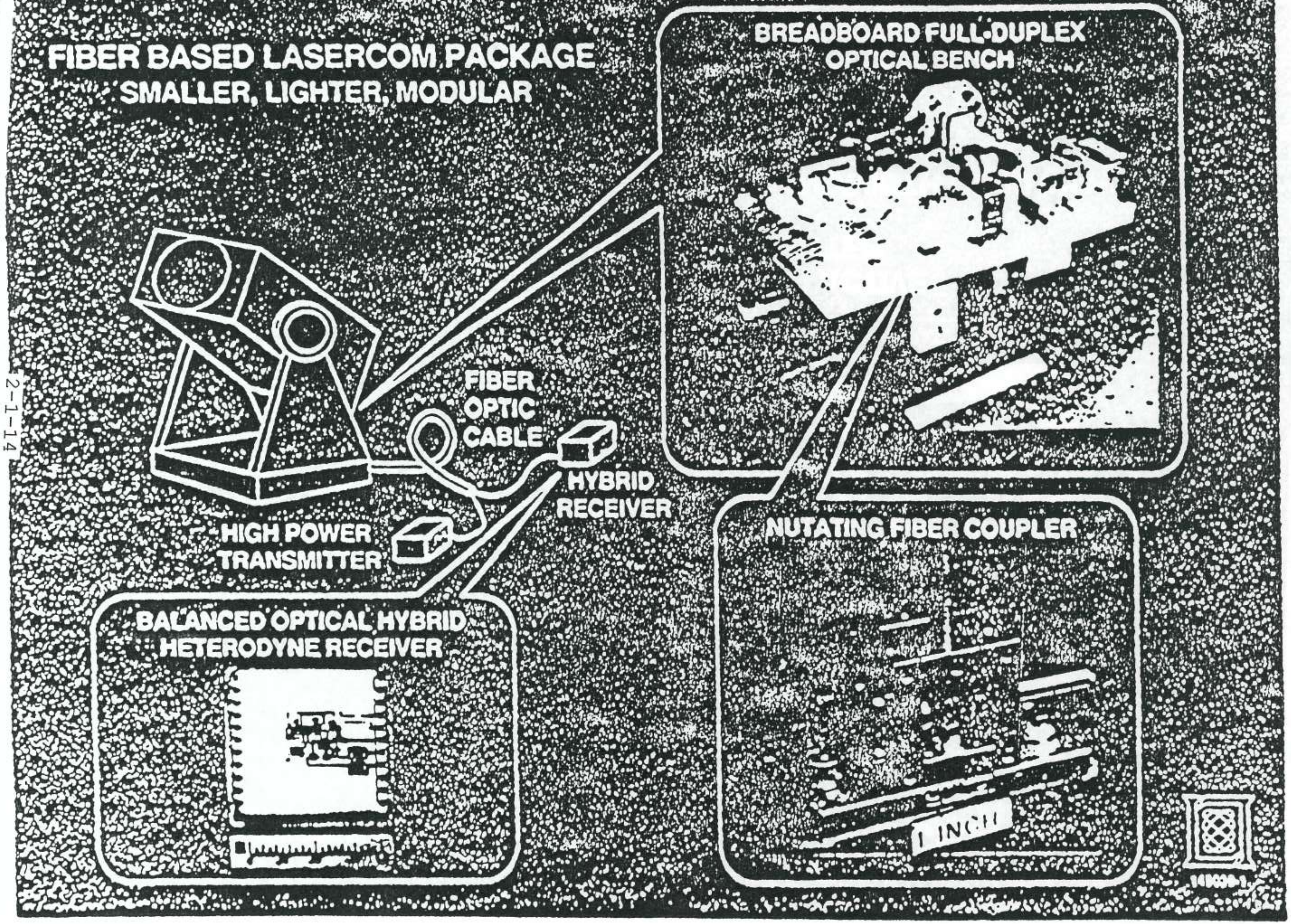


PROTOTYPE



- FAST 2-AXIS STEERING MIRROR FOR ACTIVE COMPENSATION OF SPACECRAFT JITTER
- DEMONSTRATED CLOSED-LOOP BANDWIDTH OF 10 kHz
- 20 dB REJECTION AT 1 kHz

ADVANCED LASERCOM SYSTEM DESIGN



FIBER BASED LASERCOM PACKAGE
SMALLER, LIGHTER, MODULAR

BREADBOARD FULL-DUPLEX
OPTICAL BENCH

FIBER
OPTIC
CABLE

HYBRID
RECEIVER

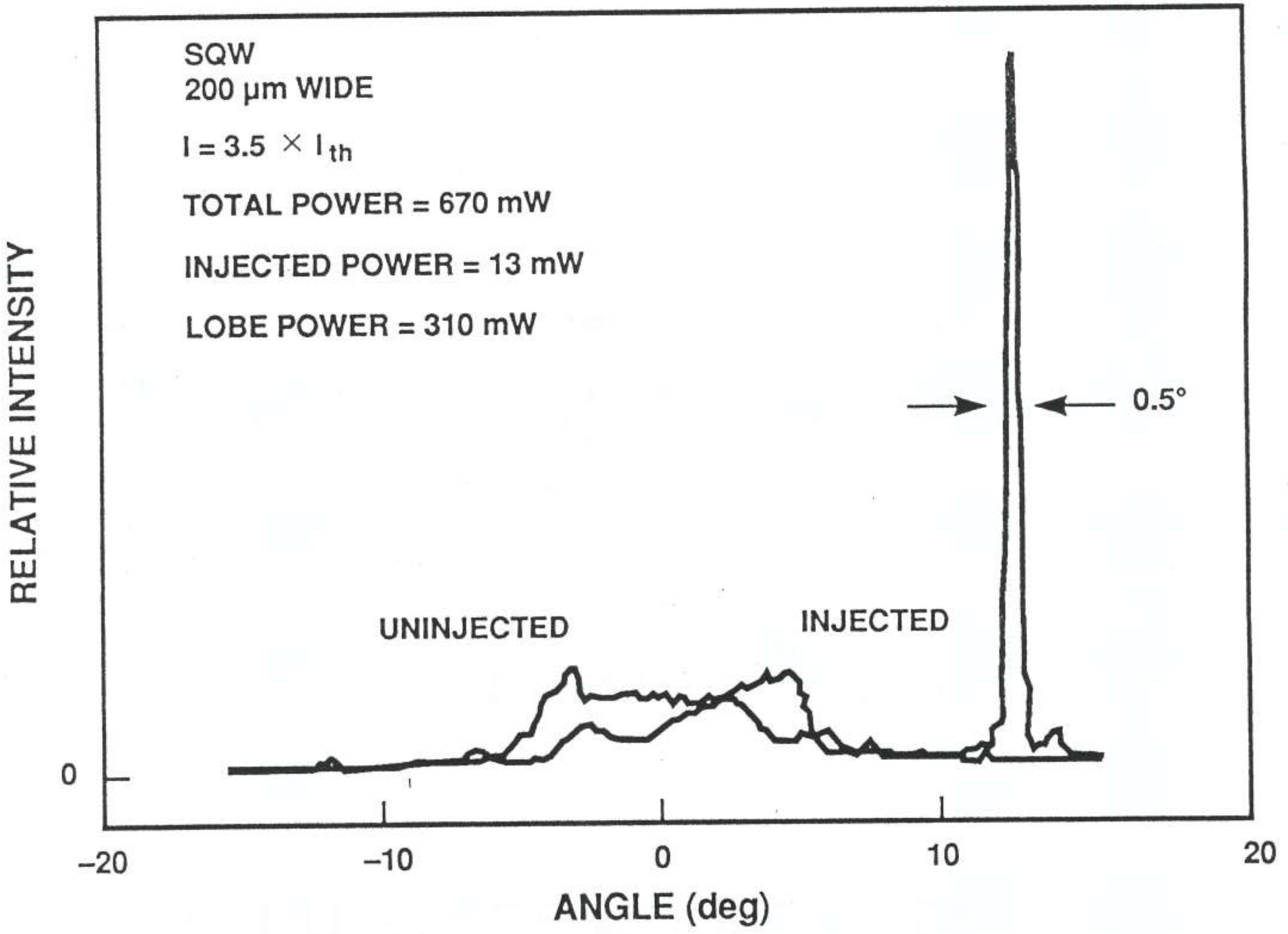
HIGH POWER
TRANSMITTER

NUTATING FIBER COUPLER

BALANCED OPTICAL HYBRID
HETERODYNE RECEIVER

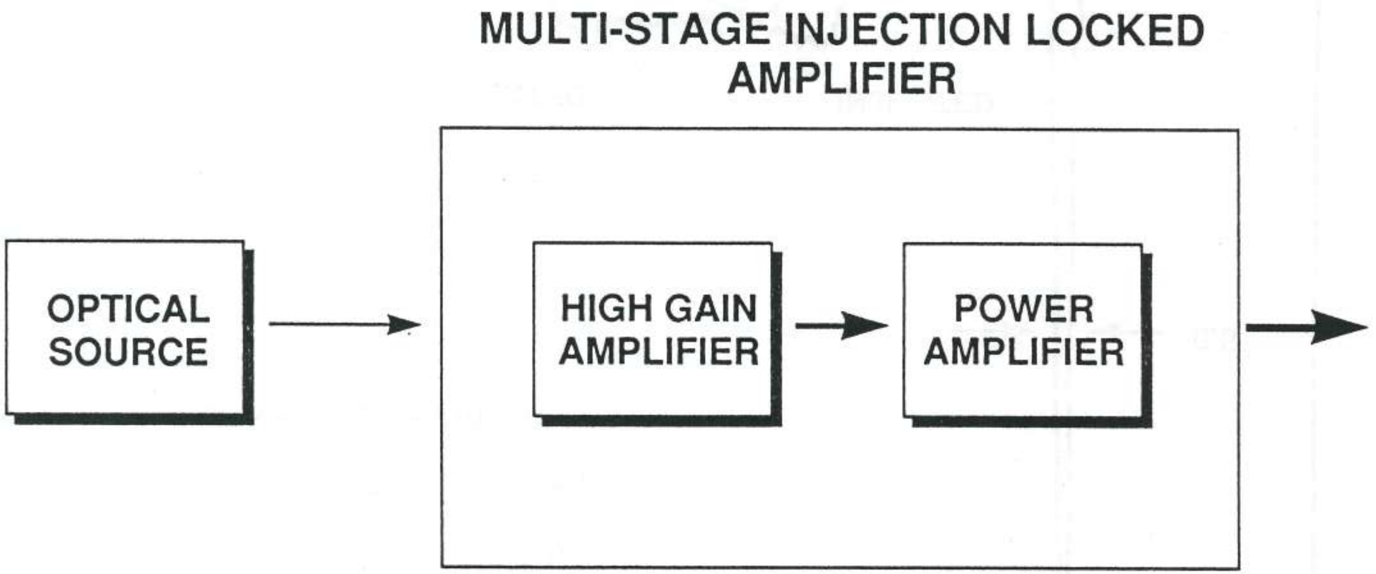
ARRAY EMISSION FAR FIELD

HIGH POWER LASER TRANSMITTER



152495-3,A

MULTI-STAGE MODULAR DESIGN



MULTI-STAGE INJECTION LOCKED AMPLIFIER

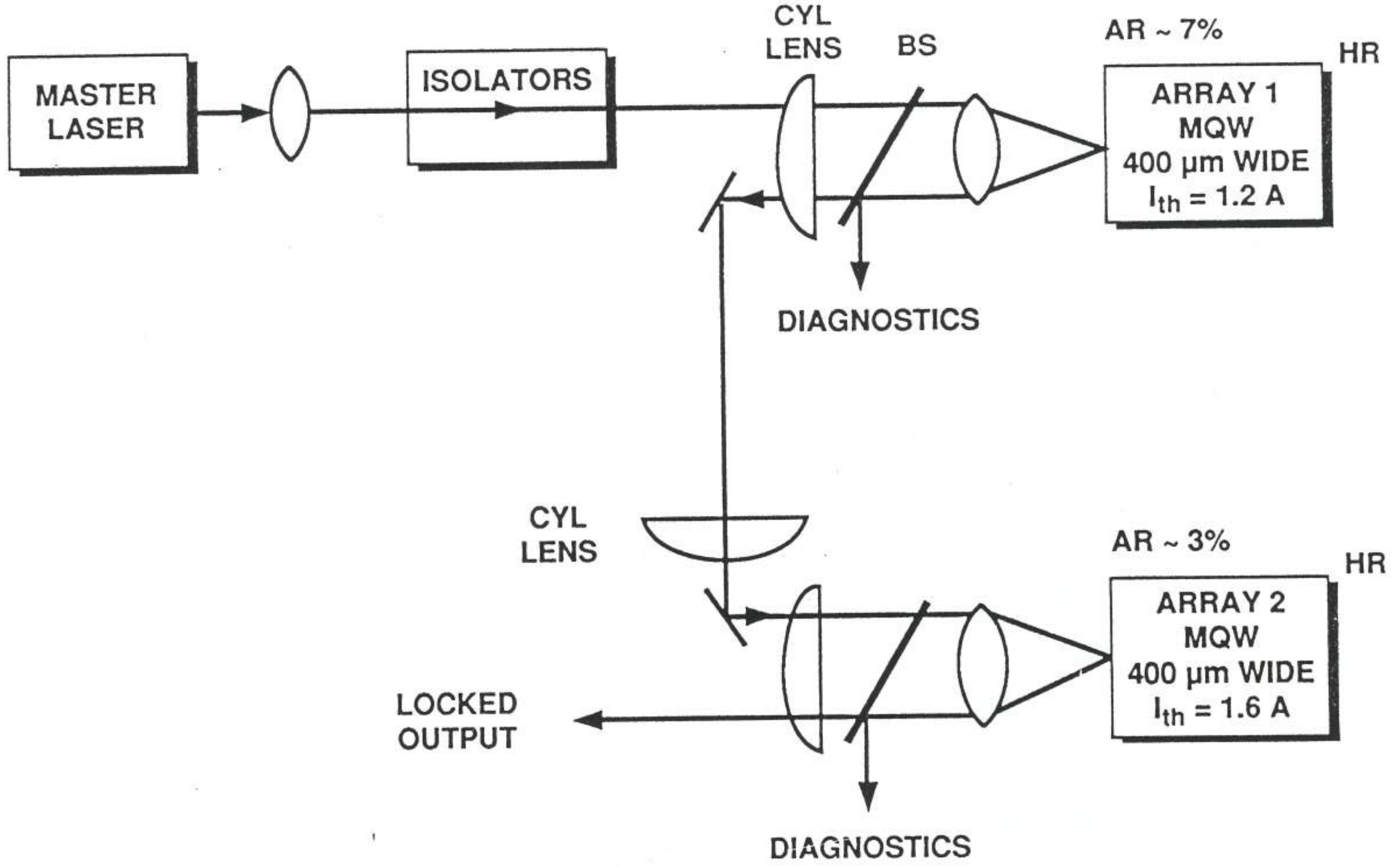
OPTICAL SOURCE

HIGH GAIN AMPLIFIER

POWER AMPLIFIER

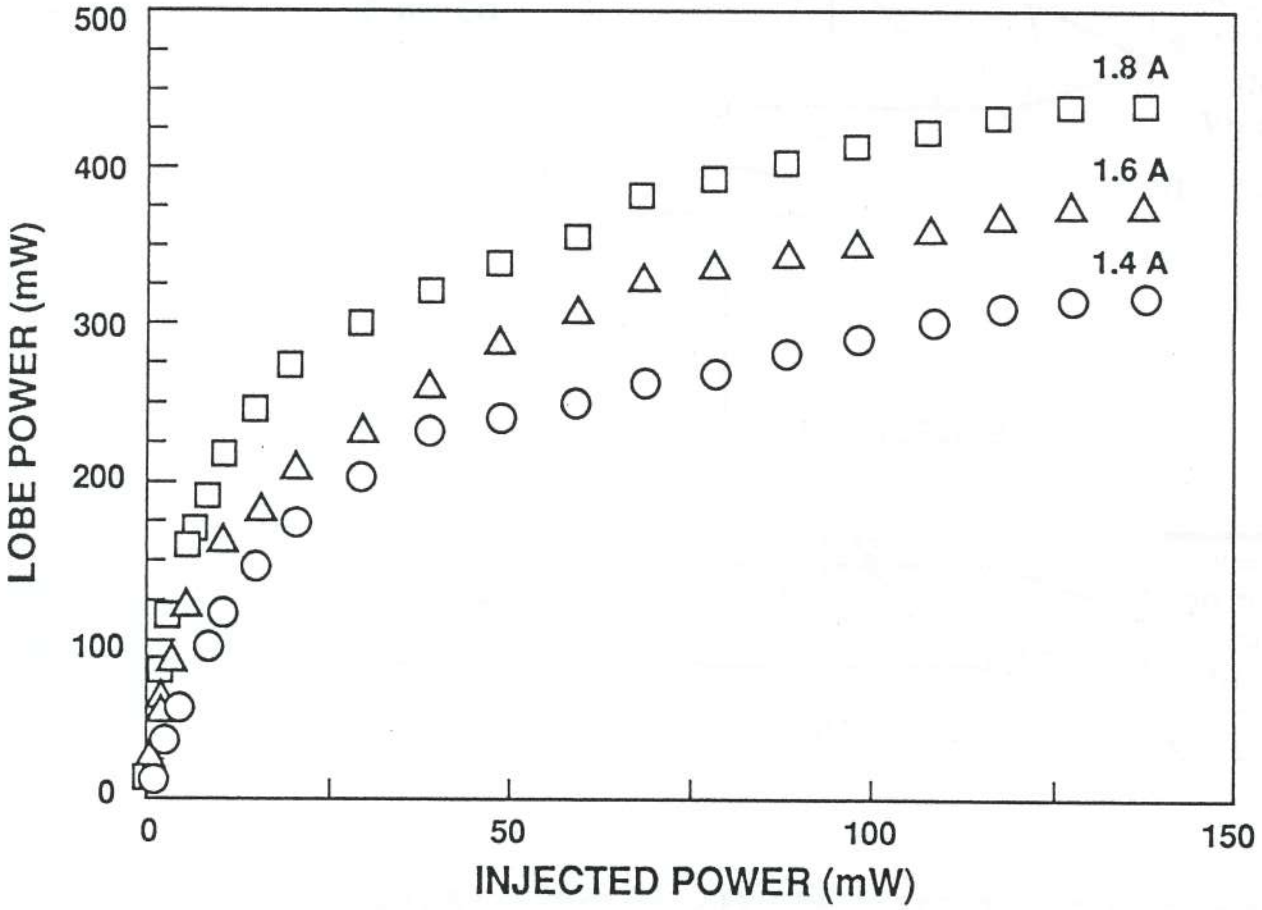
152200-1

SCHEMATIC OF THE TWO-STAGE INJECTION LOCKING EXPERIMENT



152601-2,A

TRANSFER FUNCTION OF THE SECOND STAGE INJECTION LOCKED AMPLIFIER



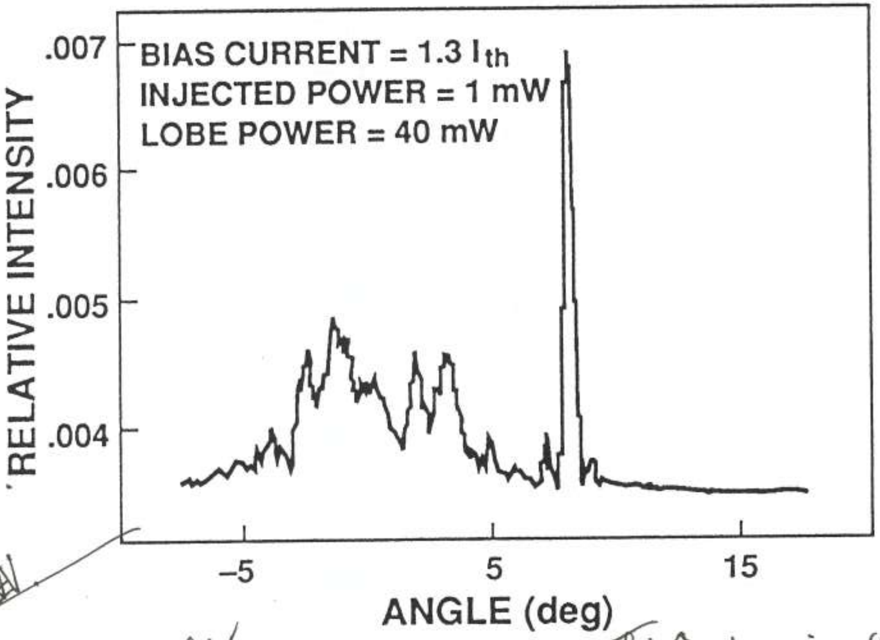
152601-1

GHz band

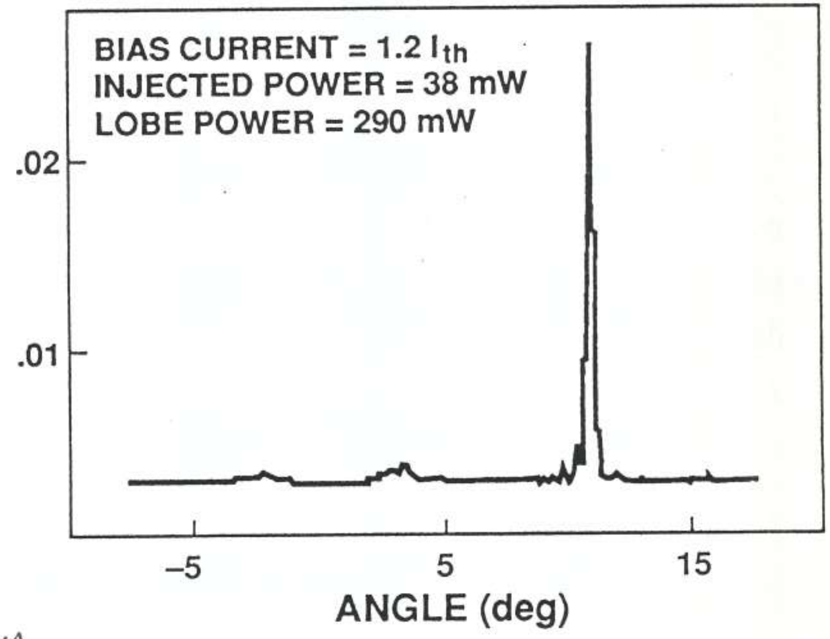
FSK
PSK

HIGH GAIN DEMONSTRATION
OVERALL GAIN = 25 dB

FIRST STAGE AMPLIFIER
FAR FIELD INTENSITY DISTRIBUTION



SECOND STAGE AMPLIFIER
FAR FIELD INTENSITY DISTRIBUTION



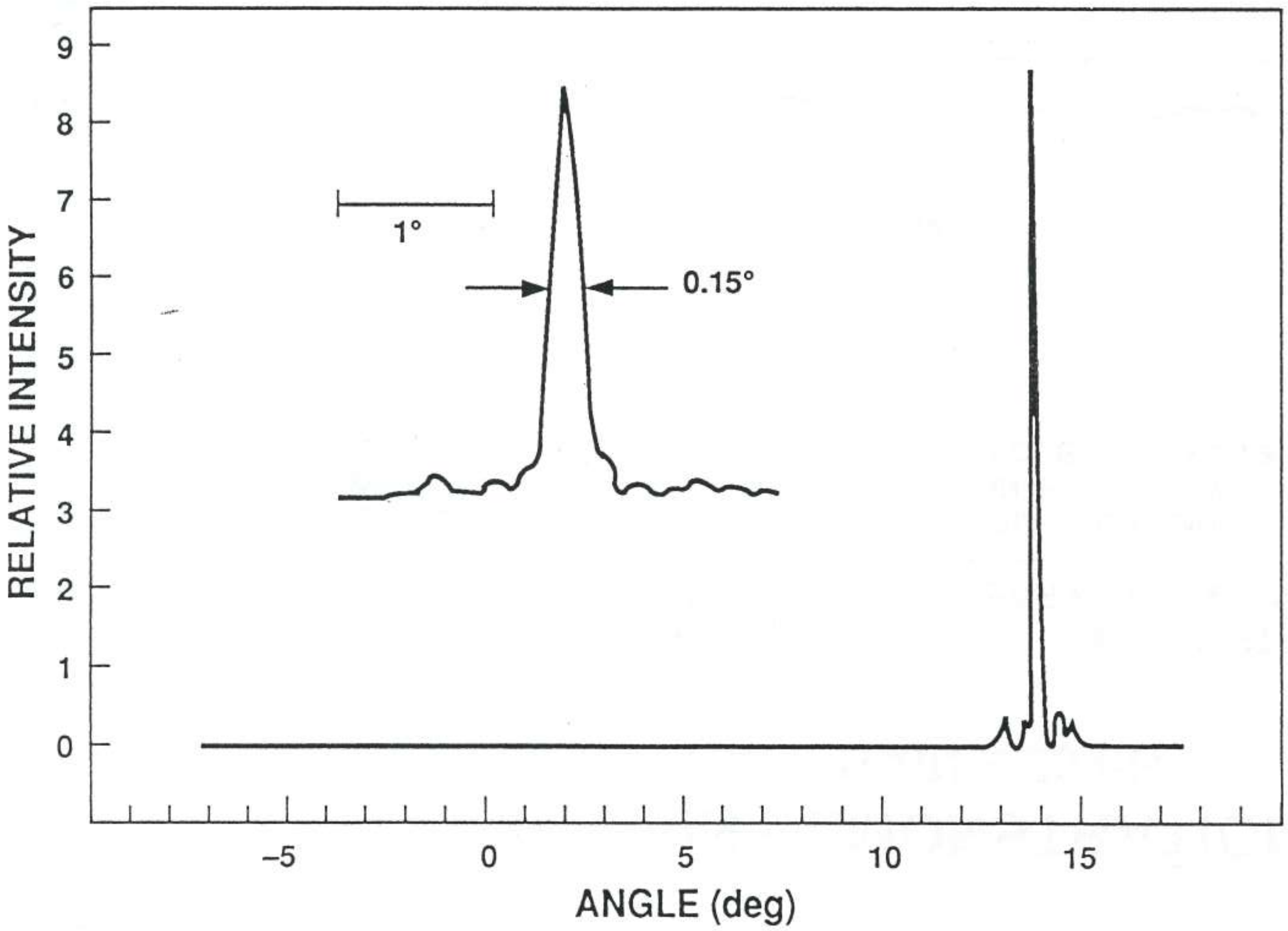
250MHz
4KHz ± 4KHz
=8KHz
Hitachi
CSP laser, Q[illegible]

1.5 µm laser

fiber optics
coupling efficiency
<1dB
single mode fiber

152753-1

FAR FIELD INTENSITY DISTRIBUTION OF THE TWO-STAGE INJECTION LOCKED AMPLIFIER



BIAS CURRENT = 1.9 A
INJECTED POWER = 20 mW
LOBE POWER = 510 mW
LOBE FRACTION = 93%

151553-2

disadvantage

single.

BW: 2~3 MHz.

degrades.

- 2 years: 4 lasers.
- error correction!

  10^{-2} error rate

contingence: laser light

- blocking noise
- locking weak signal,

CO_2

wavelength, detector size: large

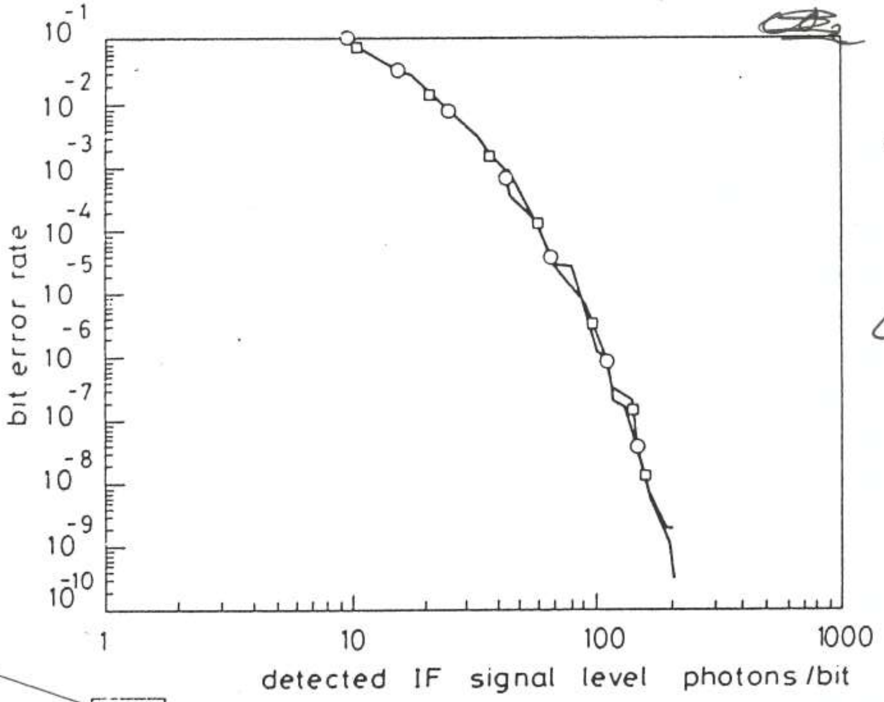
LD pumped YAG laser.

CO_2 laser radar.

20 — 60 pounds.

housing.

$LiNbO_2$:



[297/3]

Bit error rate against detected IF signal

Weigh reduction,

alignment tolerance

8 inch telescope

big coast driver

~~high power laser~~.

In-GaAs.

photo detector.

2-2

Coherent data transmission systems for optical space communications

Walter R. Leeb

Technische Universitat Wien

IWOSC '90

December 6 and 7, 1990, ATR, Kyoto

Coherent data transmission systems for optical space communications

Walter R. Leeb

Institut für Nachrichtentechnik und Hochfrequenztechnik,
Technische Universität Wien, Gusshausstrasse 25, A-1040 Wien, Austria.

The following is a summary of a presentation to be held at the "International Workshop on Optical Space Communications", Dec. 6 and 7, 1990, at ATR Optical and Radio Communications Research Laboratories, Kyoto, Japan.

In the first part I present concepts of coherent optical receivers and discuss their sensitivities and the requirements to achieve proper performance. The second part reports on some of the research activities conducted at the Technische Universität Wien within contracts for the European Space Agency. This comprises electrooptic modulators, a pilot carrier homodyne receiver, a Costas loop homodyne receiver and a heterodyne acquisition and tracking breadboard.

The difference between the three basic coherent receiver concepts known as heterodyne, homodyne, and phase diversity systems is pointed out. As examples, block diagrams for a DPSK heterodyne receiver and for PSK homodyne receivers are shown. In the latter case we distinguish between a local oscillator synchronization based on a pilot carrier, and one based on the nonlinear Costas phase-locked loop, suitable for 180° PSK modulation. Next the sensitivity limits for various coherent receivers are given as a function of laser beat linewidth.

After listing the advantages and problem areas of coherent receivers we discuss the effect of preamplifier noise not being negligible to local oscillator shot noise. We also present examples for the degradation due to background illumination and compare the coherent receiver with a direct receiver.

We have designed an electrooptic bulk modulator for $\lambda = 1.06\mu m$, based on $LiNbO_3$. Its bandwidth will be 1GHz, the optical transmission is greater than 90% at an input power of 1W, full phase modulation will require a drive power of 3.5W. On the other hand, an integrated optics modulator could successfully be operated up to 400mW of optical input power.

For a two-way transmission link breadboard at $\lambda=10\mu m$ (CO_2-laser) we have built a homodyne receiver employing a DC-coupled phase-locked loop to synchronize the local oscillator. The sensitivity was 6.7dB off the calculated one for an input signal phase-shift-modulated at 140Mbit/s with a phase deviation of $\pm 30^o$.

Presently we work on a Costas loop homodyne receiver for the PSK modulated radiation of Nd:YAG lasers. For optical preprocessing we will employ a six-port 90^o hybrid feeding two balanced detectors which in turn feed the in-phase and the quadrature arm of the Costas receiver. Measurement of the frequency noise spectral density of the diode-pumped monolithic ring lasers revealed a low linewidth (≈0.35Hz) and reasonable $1/f^2$-noise. Calculation of the loop's noise power show that some 100pW of optical input power are needed for the synchronization process.

A laboratory model of a receiver for coherent acquisition and tracking based on DFB semiconductor lasers at $\lambda=1.55\mu m$ was completed. The intermediate frequency was set to 700 MHz. The quadrant position detector relies on four pin InGaAs diodes which are fed by the superimposed input and local beams after being split into four by a reflecting pyramid. A noise-equivalent angle of 6μ rad was achieved. A total acquisition time of a few seconds was measured under transverse movement of the transmitter.

BIOGRAPHY

Walter R. Leeb was born in Vienna, Austria, on April 11, 1942. He received the M.S. and Ph.D. degrees in electrical engineering (communications) from the Technische Universität Wien, Vienna, Austria, in 1966 and 1972, respectively.

In 1966 he joined the Institut für Hochfrequenztechnik of the Technische Universität Wien as a Research Assistant, became Assistant Professor in 1969, and was appointed Associate Professor at the Institut für Nachrichtentechnik und Hochfrequenztechnik in 1982. In 1974 and 1975 he was awarded a National Research Council Postdoctoral Research Associateship which he spent at Laser Technology Branch, NASA/Goodard Space Flight Center, Greenbelt, MD. Since 1972 he has been a lecturer at the Technische Universität Wien for Optical Communications. He was engaged in the field of diffraction theory, electrooptic modulators, and optical homodyne reception. Presently he works in the field of optical communications with emphasis on optical intersatellite link programs based on diode lasers and Nd:YAG lasers.

COHERENT DATA TRANSMISSION SYSTEMS FOR OPTICAL SPACE COMMUNICATIONS

Walter R. Leeb

Institut für Nachrichtentechnik und Hochfrequenztechnik
Technische Universität Wien, Austria

CONTENTS

I. COHERENT OPTICAL RECEIVERS

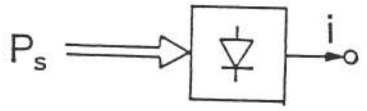
- * CONCEPTS
- * SENSITIVITIES
- * REQUIREMENTS

II. ACTIVITIES AT TECHN. UNIV. WIEN

- * ELECTROOPTIC MODULATORS
- * PILOT CARRIER HOMODYNE RECEIVER
- * COSTAS LOOP HOMODYNE RECEIVER
- * HETERODYNE ACQUISITION AND TRACKING

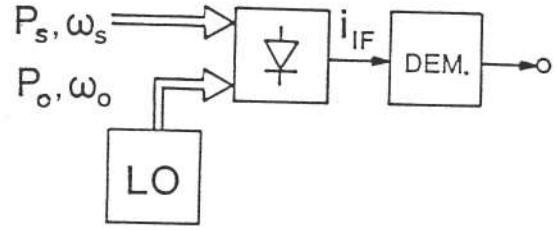
RECEIVER CONCEPTS

DIRECT DETECTION



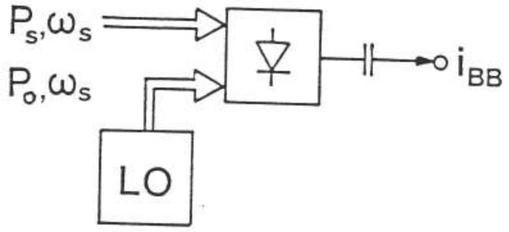
$i \propto P_S$

HETERODYNING



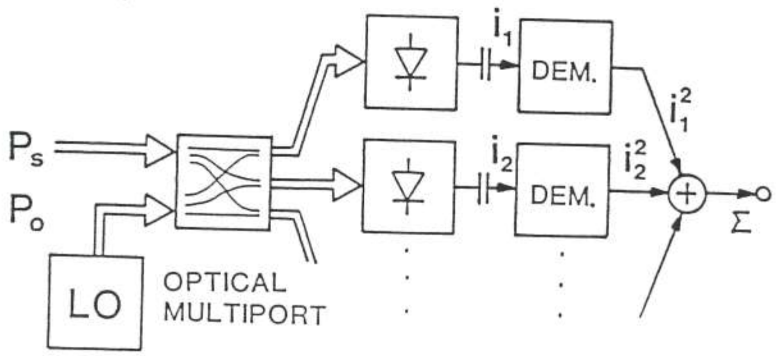
$i_{IF} \propto \sqrt{P_S P_o} \cos[(\omega_S - \omega_o)t + \varphi]$

HOMODYNING



$i_{BB} \propto \sqrt{P_S P_o} \cos\varphi$

PHASE DIVERSITY



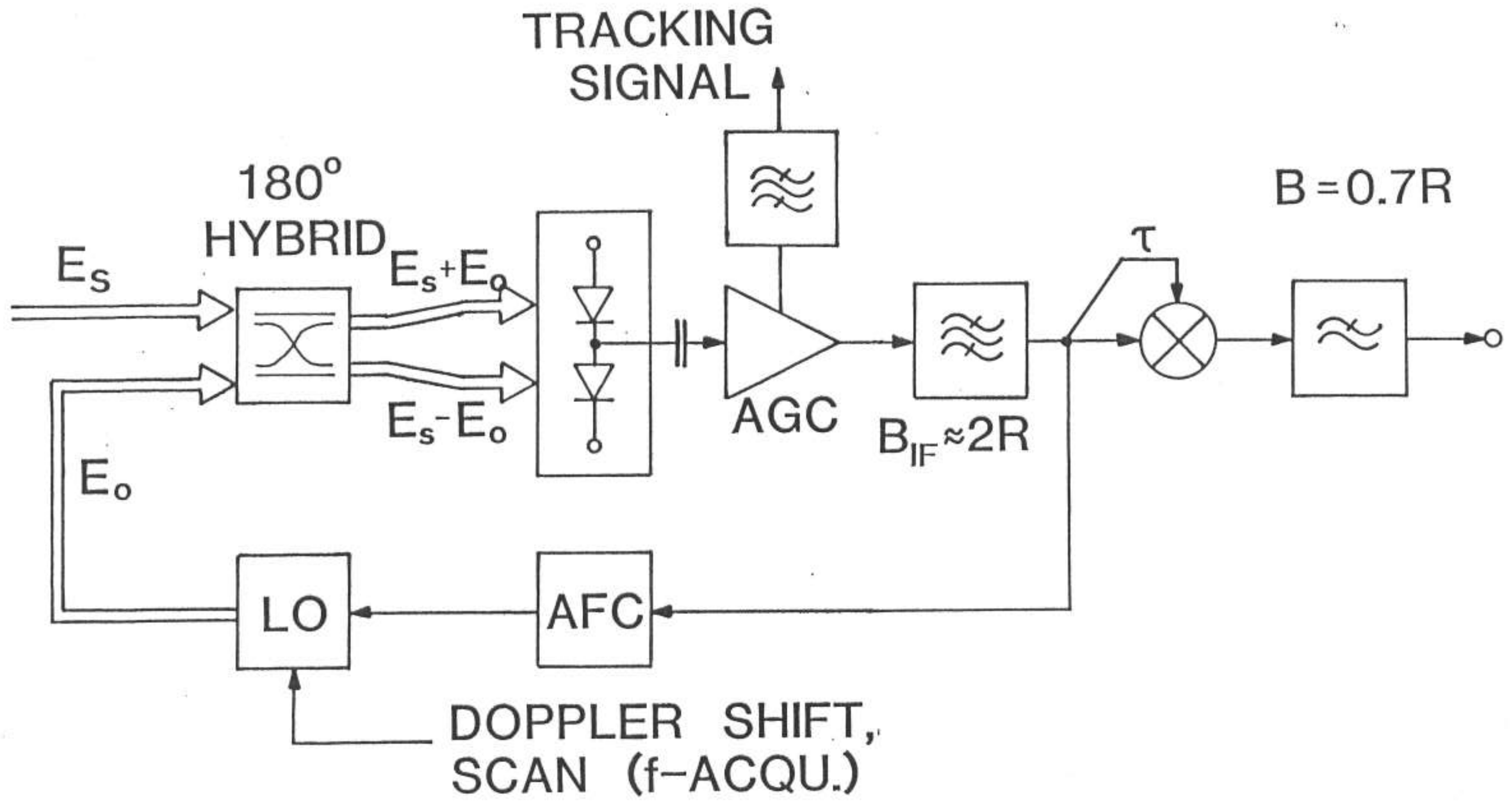
$i_1 \propto \sqrt{P_S P_o} \cos\varphi_1(t)$

$i_2 \propto \sqrt{P_S P_o} \cos(\varphi_1(t) + \Delta)$

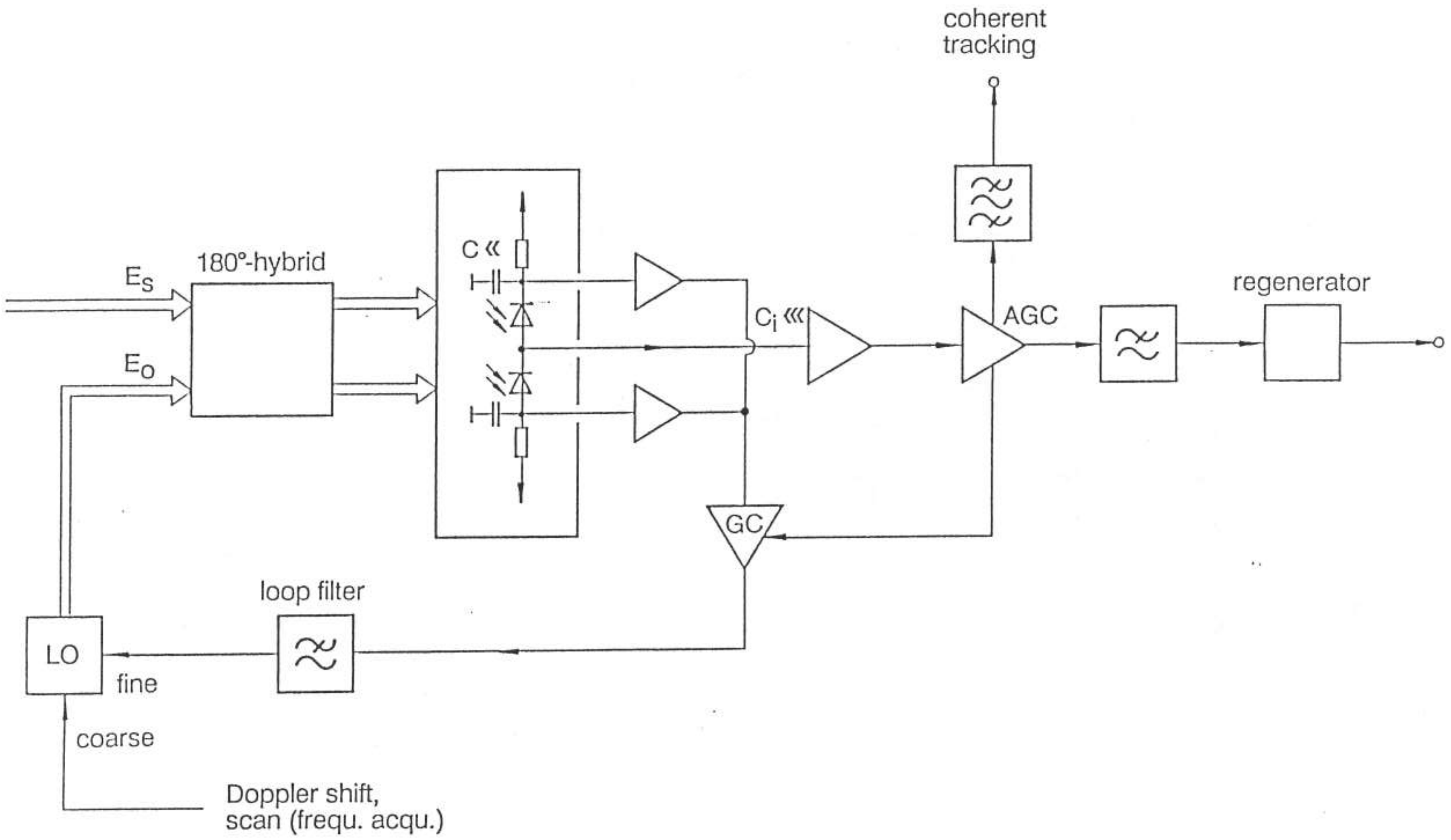
⋮

$\Sigma \propto P_S P_o$

DPSK HETERODYNE RECEIVER

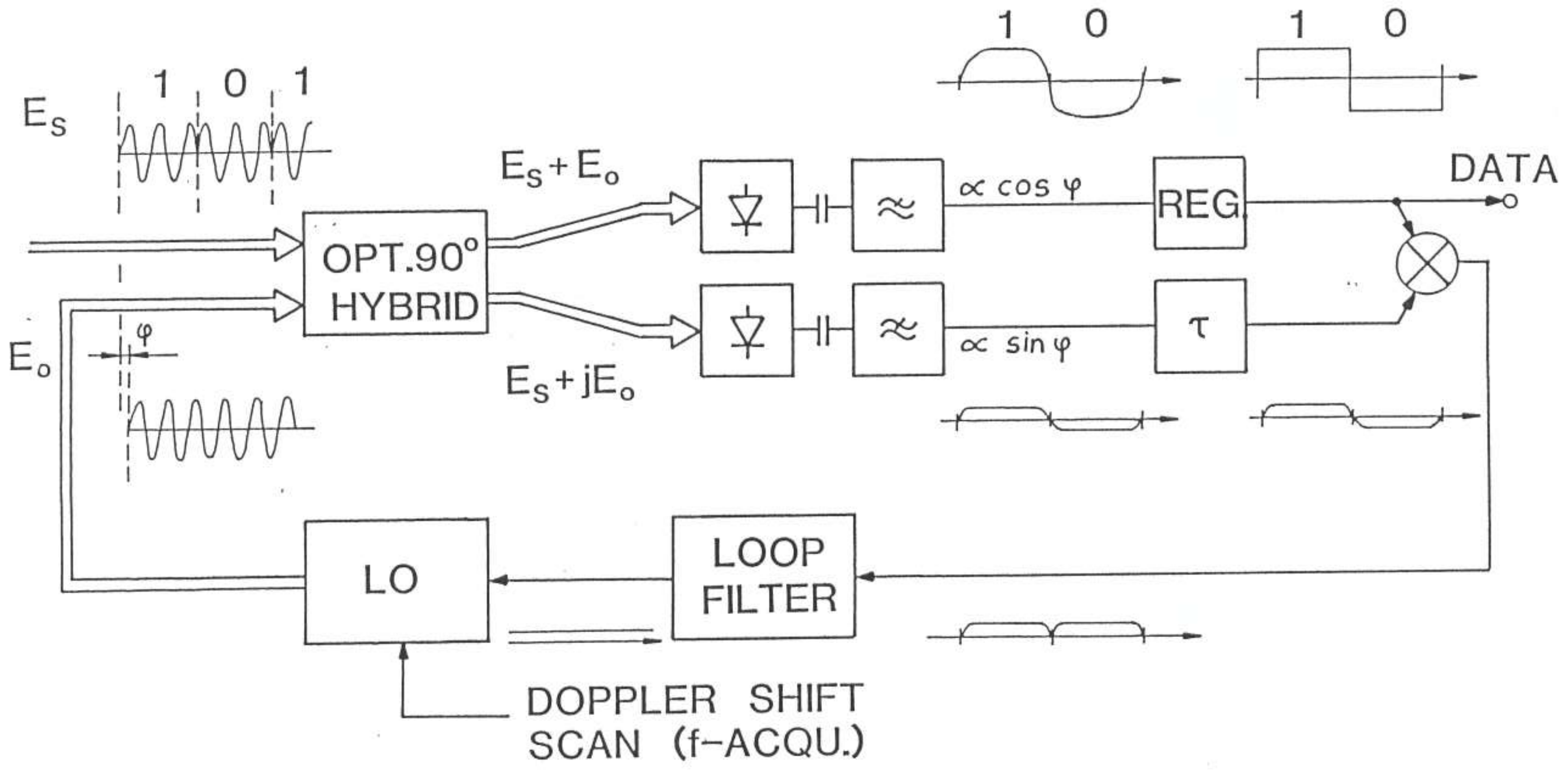


HOMODYNE PSK PILOT CARRIER RECEIVER



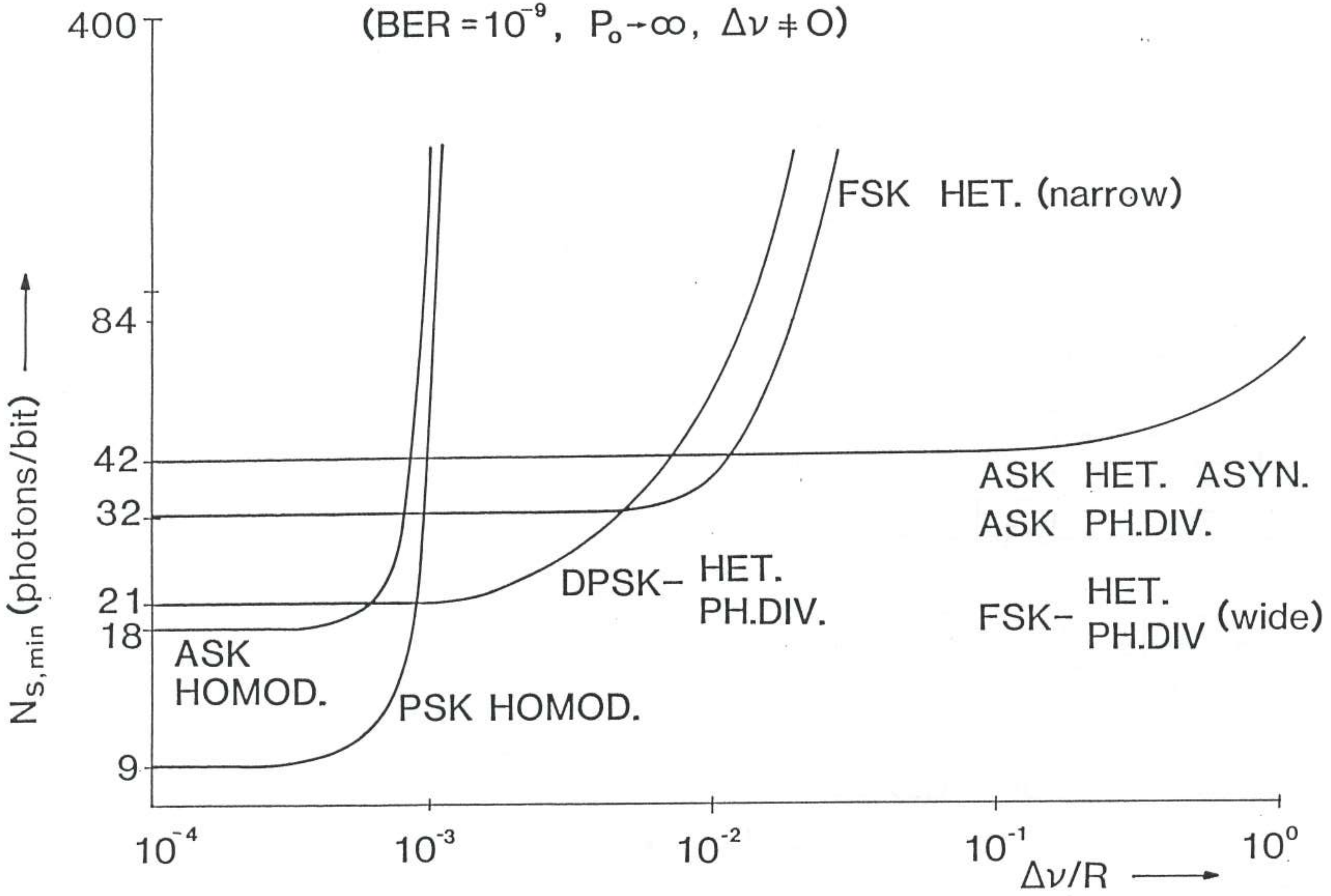
PSK HOMODYNE

(DECISION-DRIVEN COSTAS PHASE-LOCKED LOOP)



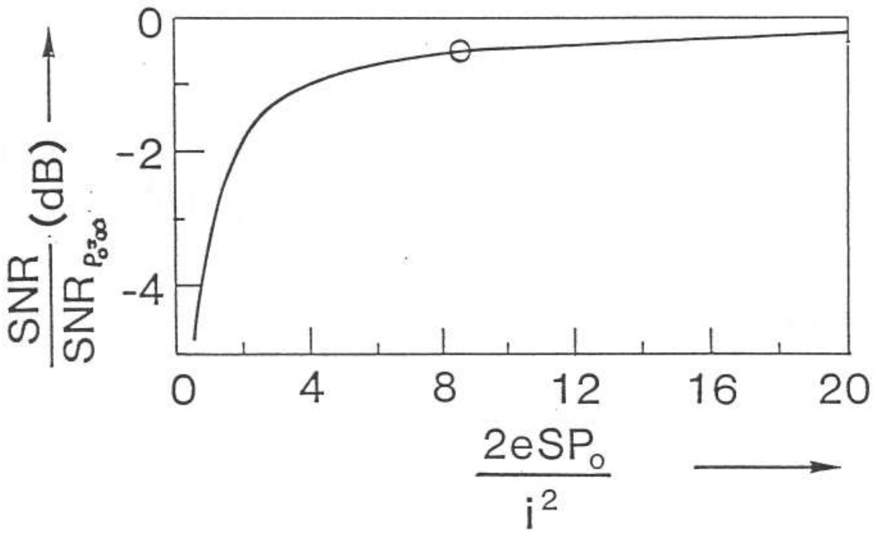
RECEIVER SENSITIVITY

($BER = 10^{-9}$, $P_o \to \infty$, $\Delta\nu \neq 0$)



LO POWER $\neq \infty$

$$\mathrm{SNR} = \frac{\text{Signal}}{\text{Shot noise} + \text{Circuit noise}} = \frac{\mathrm{SNR}_{P_o=\infty}}{1 + \frac{i^2}{2eSP_o}}$$



EXAMPLE:

$i = 5\mathrm{pA}/\sqrt{\mathrm{Hz}}$, $P_o = 1\mathrm{mW}$, $S = 0.8\mathrm{A/W}$

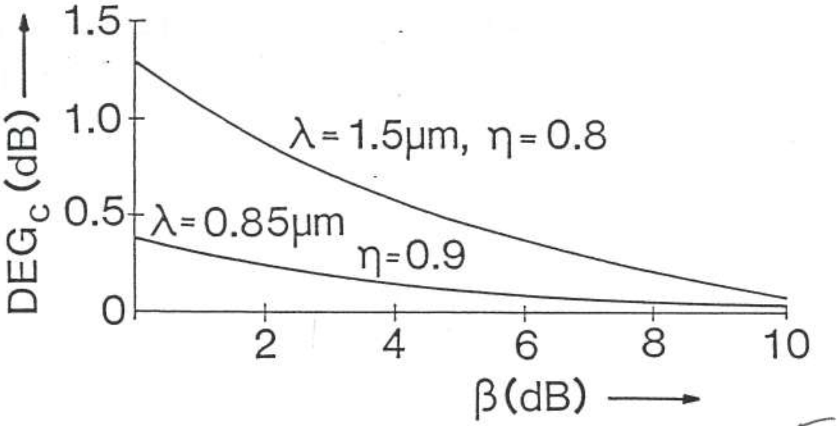
$\Downarrow$

$\boxed{-0.5\mathrm{dB}}$

BACKGROUND

SUN

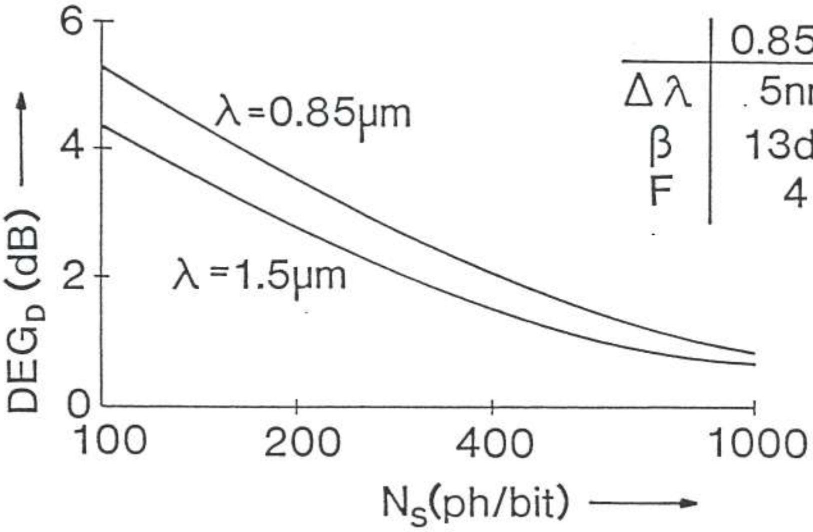
- COHERENT RECEIVER, OPERATING β dB ABOVE SHOT NOISE LIMIT



degradation in dB

diffraction limit

- DIRECT DETECTION $\Omega_{FV}/\Omega_{DL}=10$, R = 500Mbit/s



	0.85μm	1.5μm
Δλ	5nm	8nm
β	13dB	16dB
F	4	1

COHERENT RECEPTION:

BENEFITS AND REQUIREMENTS/PROBLEMS

⊕ INPUT POWER SENSITIVITY

⊕ MODULATION FORMATS LIKE FSK, PSK

⊕ LESS SENSITIVE TO BACKGROUND

⊕ ISOLATION IN TWO-WAY LINK

⊕ MULTI-CHANNEL TRANSMISSION

⊕ HIGH DYNAMIC RANGE

⊖ LASER SPECTRAL PURITY

⊖ LOCAL OSCILLATOR
  - tunability (Doppler)
  - sufficient power
  - beam matching
  - phase noise
  - intensity noise

⊖ SMALL FIELD OF VIEW

⊖ FREQUENCY/PHASE ACQUISITION

⊖ COMPLEXITY

COHERENT SYSTEMS - ACTIVITIES AT TECHN. UNIV. WIEN

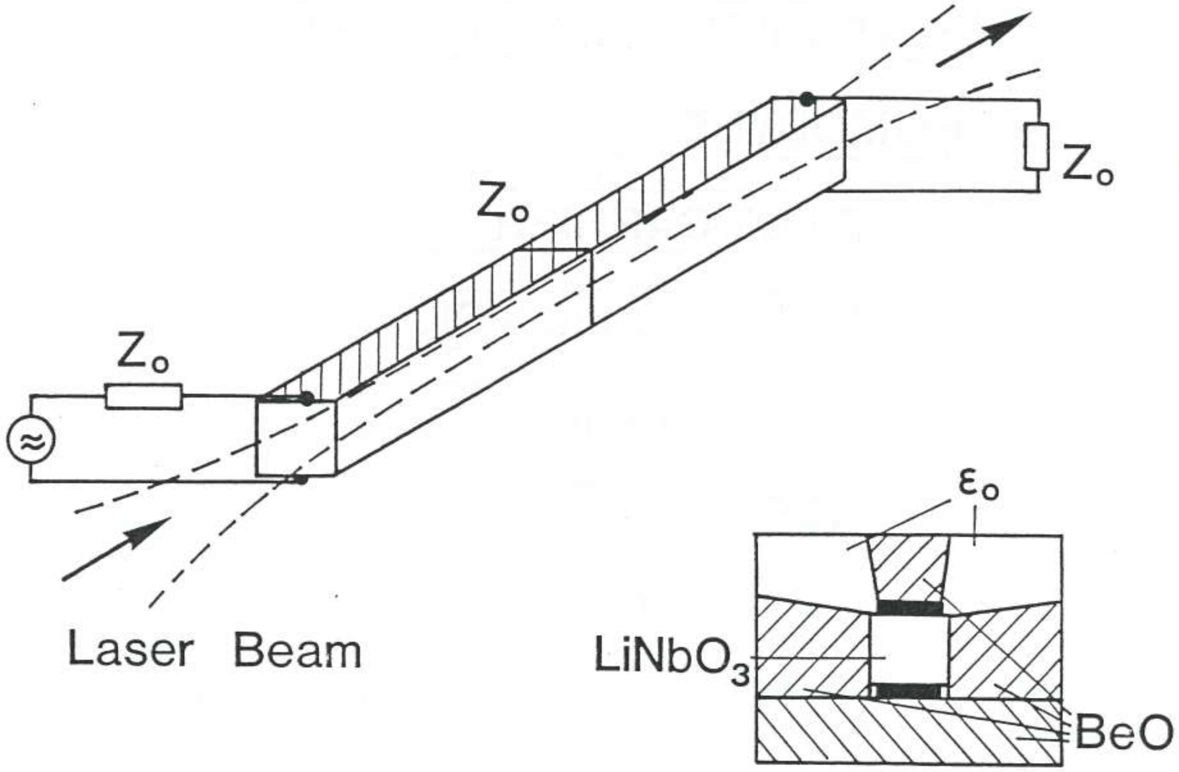
- **DEVICES**
  - **ELECTROOPTIC MODULATORS**
    - **$\lambda = 10\mu m$, CdTe**
    - **$\lambda = 1\ \mu m$, $LiNbO_3$**
      - **BULK**
      - **INTEGRATED OPTICS**
  - **90° HYBRIDS**
  - **LASER FREQUENCY NOISE**

continued

- SYSTEMS
  - BACKGROUND RADIATION
  - RECEIVERS
    - HETERODYNE, $\lambda = 1\ \mu m$, ASK
    - HOMODYNE
      - PILOT CARRIER
        - $\lambda = 10\ \mu m$, PSK
        - $\lambda = 1\ \mu m$, ASK
      - COSTAS LOOP
        - $\lambda = 10\ \mu m$
        - $\lambda = 1\ \mu m$
  - ACQUISITION AND TRACKING
    - DIRECT DETECTION, $\lambda = 0.85\ \mu m, 1.3\ \mu m$
    - HETERODYNE DETECTION, $\lambda = 1.55\ \mu m$

ELECTROOPTIC MODULATORS FOR 1μm

BULK MODULATOR



OPTICAL: GAUSSIAN BEAM
ELECTRICAL: TRAVELING WAVE
DIMENSION: 0.5mm x 0.5mm x 80mm

CALCULATED PROPERTIES

BANDWIDTH	1 GHz
IMPEDANCE	35 Ω
HALF-WAVE VOLTAGE	22 V
DRIVE POWER	3.5 W
POWER HANDLING	> 1W
INSERTION LOSS	< 0.4 dB
MASS	< 500 g

INTEGRATED OPTICS MODULATOR at $\lambda = 1.06 \mu m$

$LiNbO_3$

Ti- indiffused
y-cut, x-propagating

Pig tailing

Polarization-preserving monomode fiber,
(HB 1000, York)

Half-wave voltage

3.5 to 5 V
(≙ 0.06 to 0.13 W into 50 Ω)

Insertion loss

4.3 to 7 dB

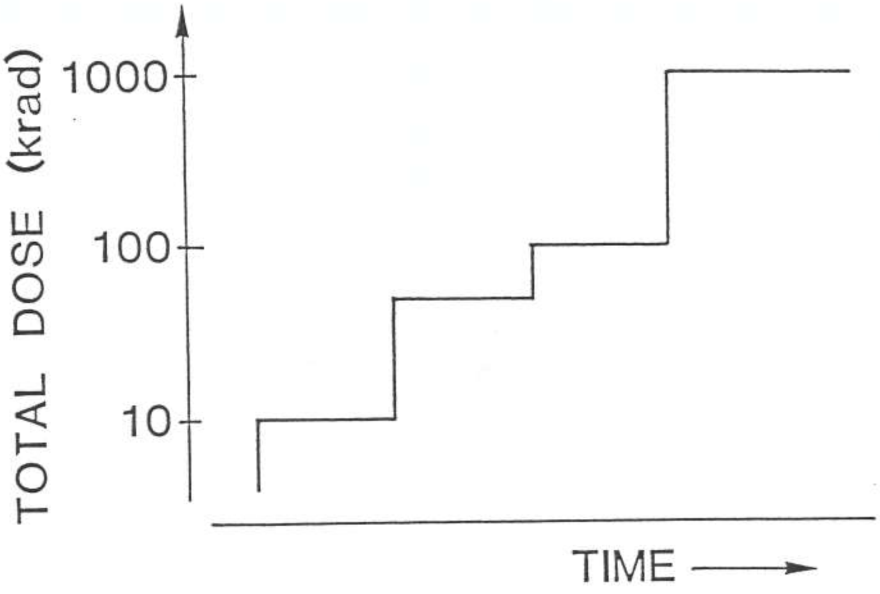
Power handling

>400 mW into $LiNbO_3$ chip
(≙ MW/cm^2)

RADIATION HARDNESS OF $LiNbO_3$

SAMPLE: 25mm long (z-axis), 2mm diam

SOURCE: Co^{60}



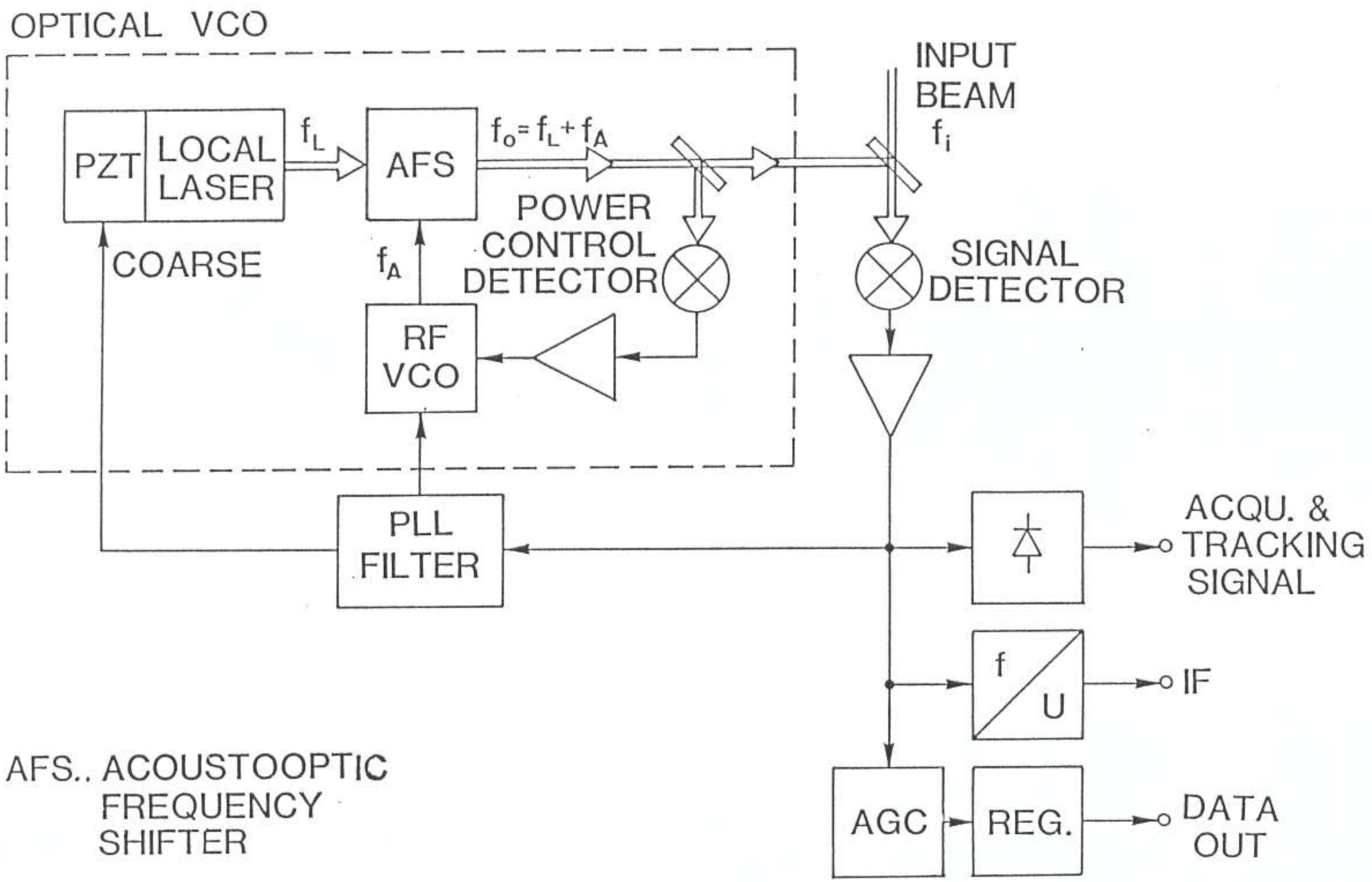
NO CHANGE OF TRANSMISSION AT λ=1.06µm

PILOT CARRIER HOMODYNE RECEIVER

SPECIFICATIONS:

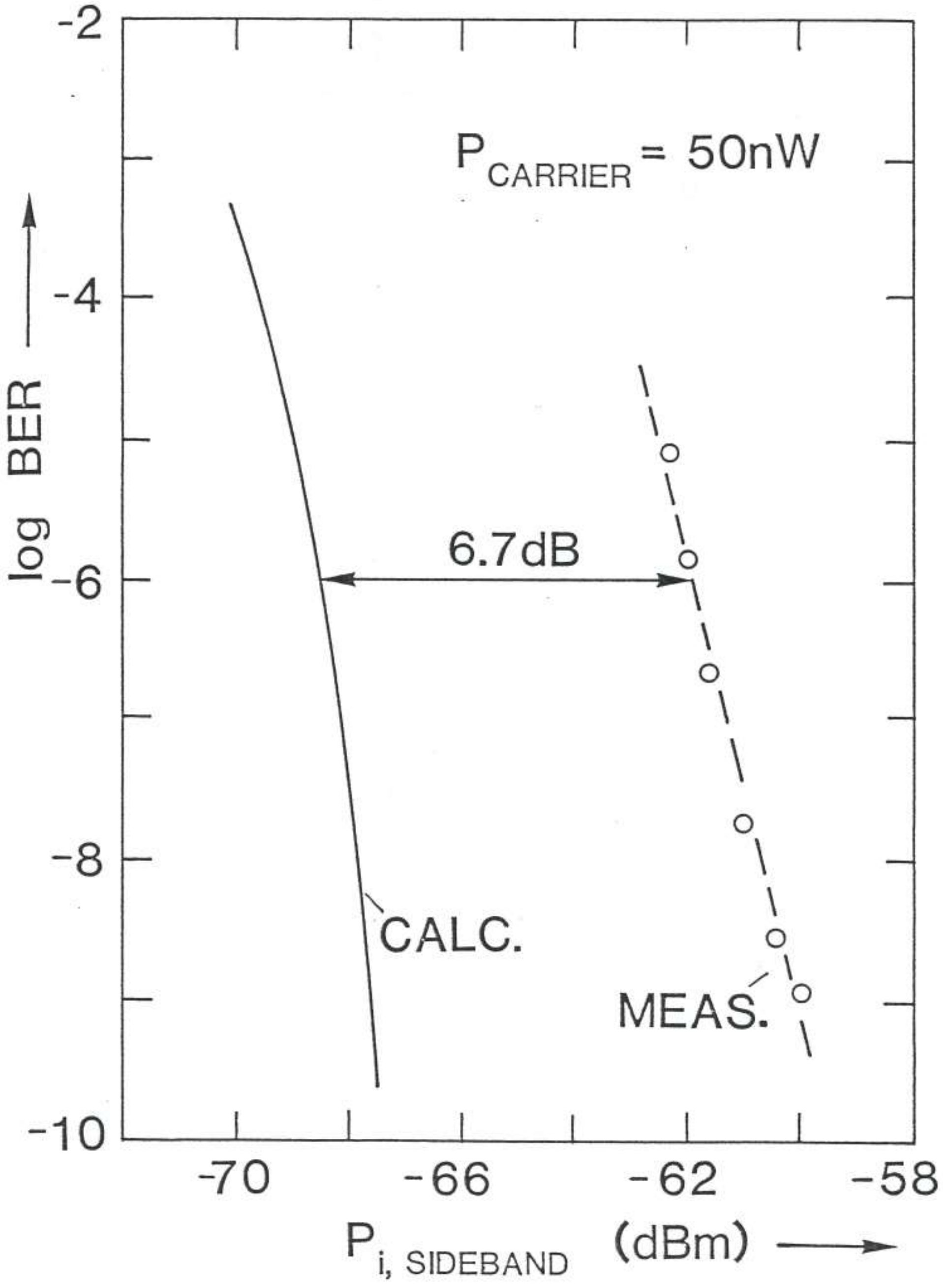
Wavelength:	$\lambda = 10.591\,\mu m$ (CO_2 laser)
Local oscillator synchronization:	DC-coupled phase-locked loop (PLL), single detector
Modulation:	digital phase modulation with residual carrier (PSK,$\Delta\varphi < 90^o$)
Data rate:	140 Mbit/s
Data format:	NRZ
Input power	
residual carrier:	$\geq$- 73 dBW ($\geq$50nW)
sideband power:	$\geq$- 90 dBW ($\geq$1 nW) for BER = 10^{-6}

RECEIVER BLOCK DIAGRAM



AFS.. ACOUSTOOPTIC FREQUENCY SHIFTER

10μm PILOT CARRIER HOMODYNE RECEIVER



Homodyne Rx.

COSTAS LOOP RECEIVER FOR $\lambda = 1\,\mu m$

LASERS

ND:YAG, $\lambda = 1.064\,\mu m$, LINEWIDTH ≈ 0.5 Hz
POWER = 5 to 300 mW

DATA:

140 Mbit/s, PSK, BER = 10^{-9}

PHOTODIODES

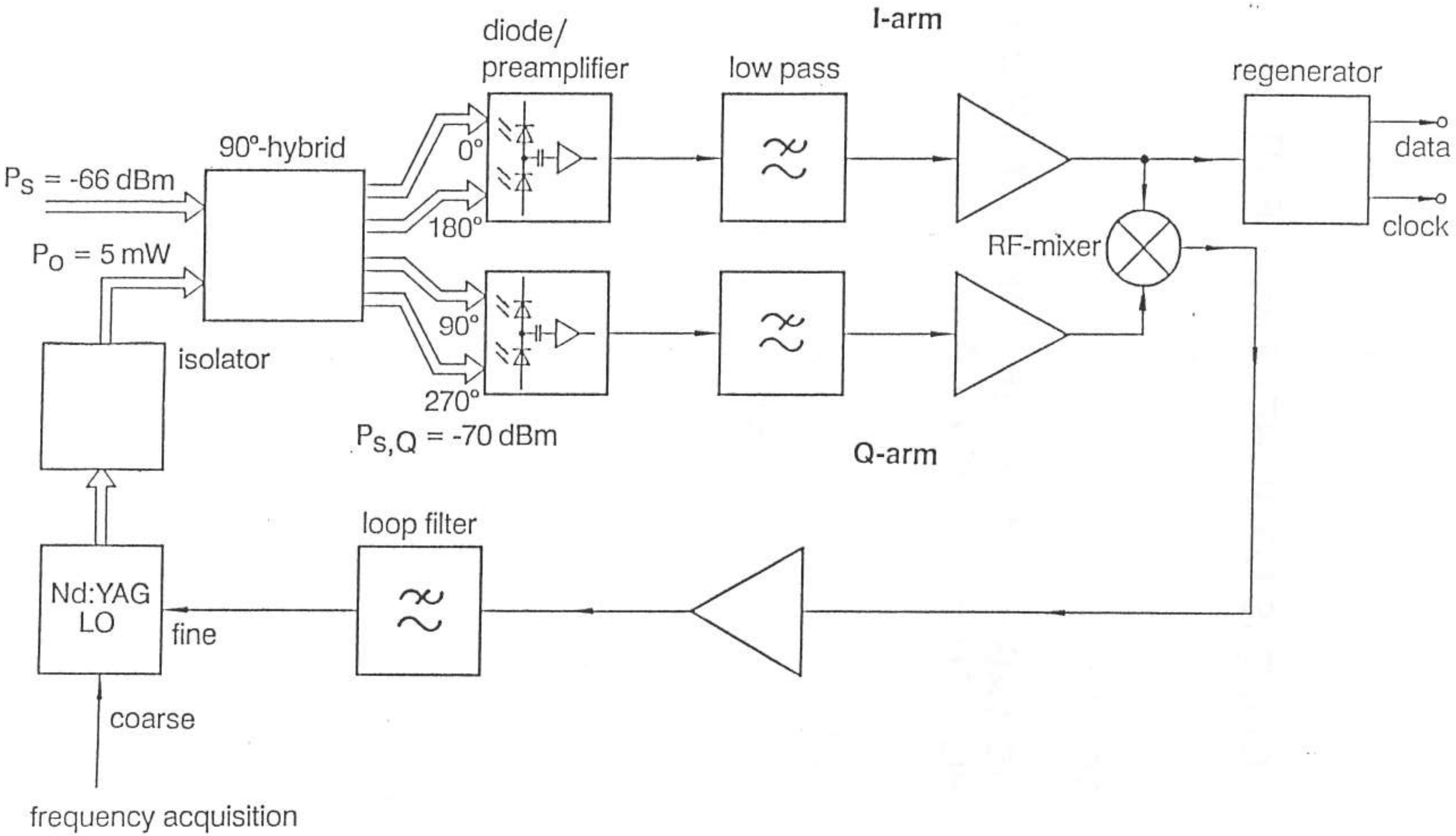
InGaAs, $\eta = 82\%$

SENSITIVITY

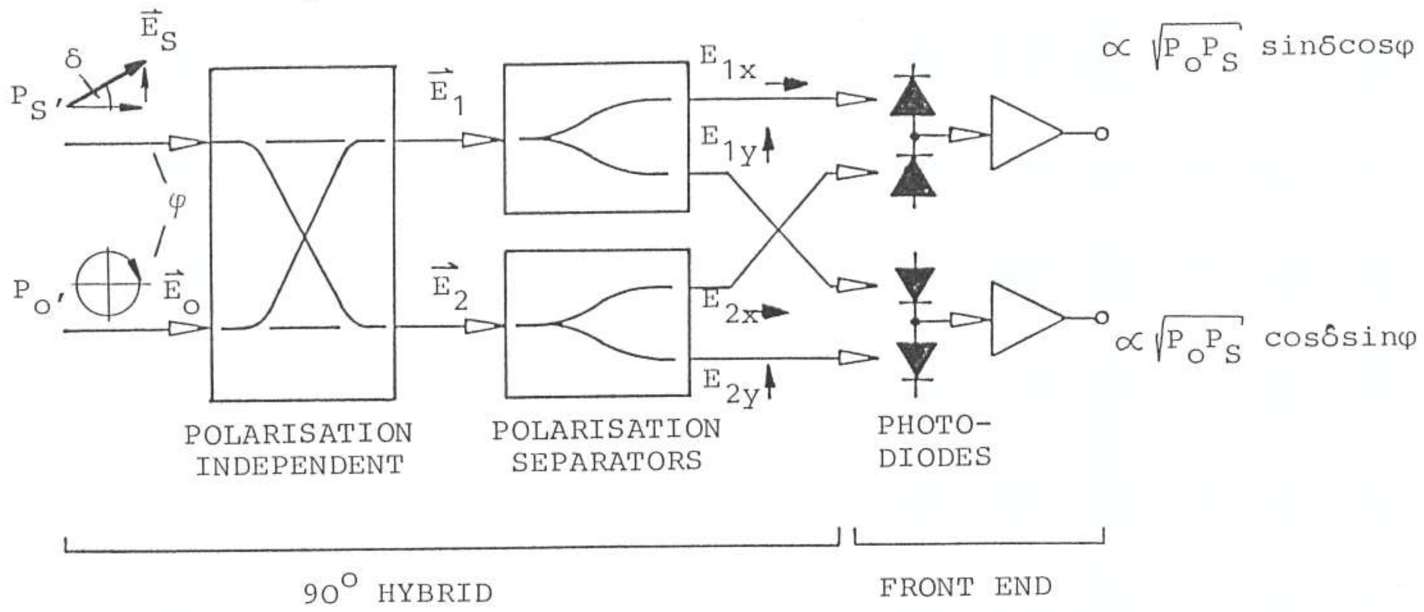
$P_{i,IDEAL} = 0.24 nW \mathrel{\widehat{=}} -66.3 dBm$

$P_{i,EXPECTED} \approx -60.5$ dBm

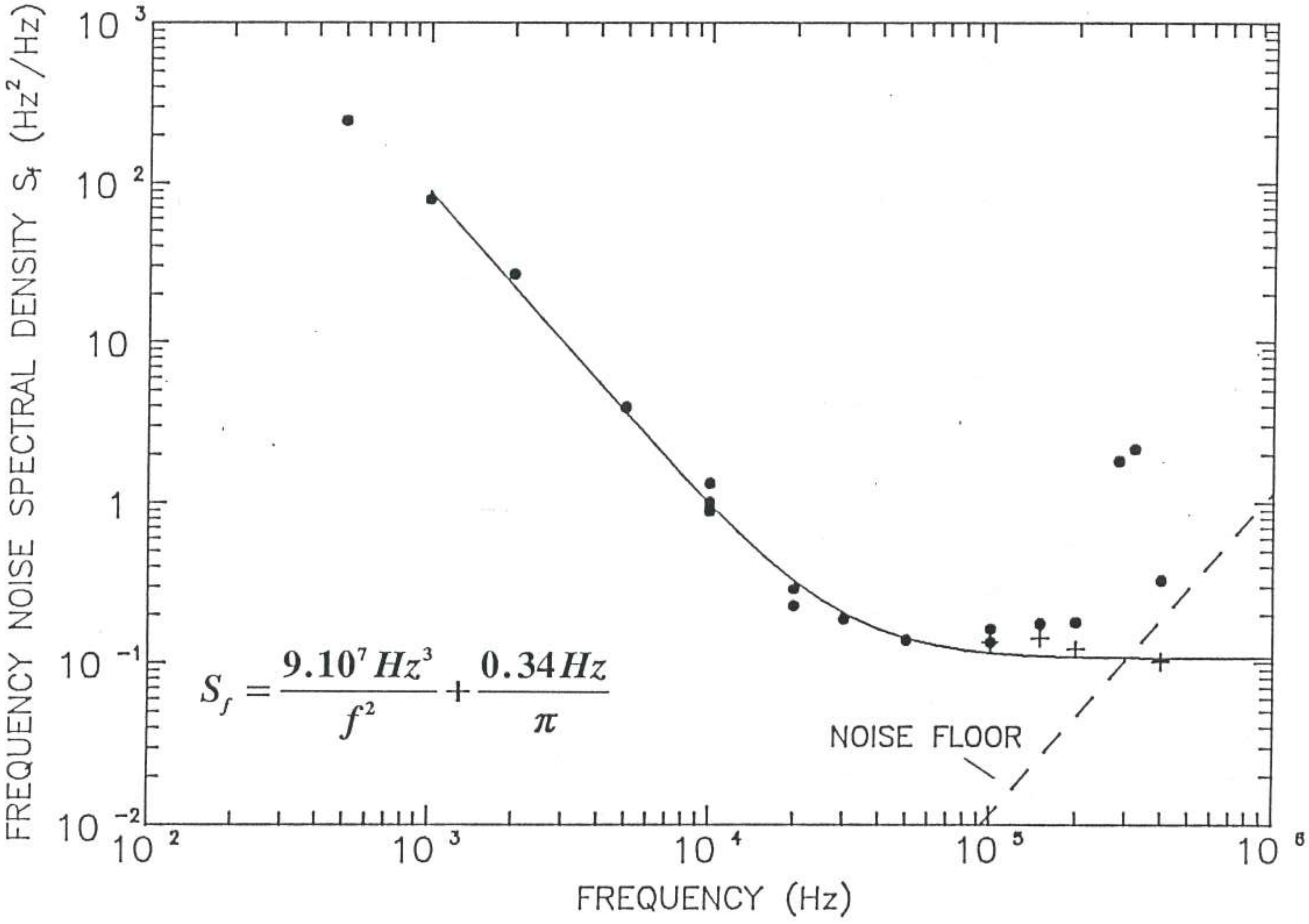
RECEIVER BLOCK DIAGRAM



SIX-PORT 90° HYBRID AND BALANCED FRONT END



MONOLITHIC DIODE-PUMPED ND:YAG RING LASER

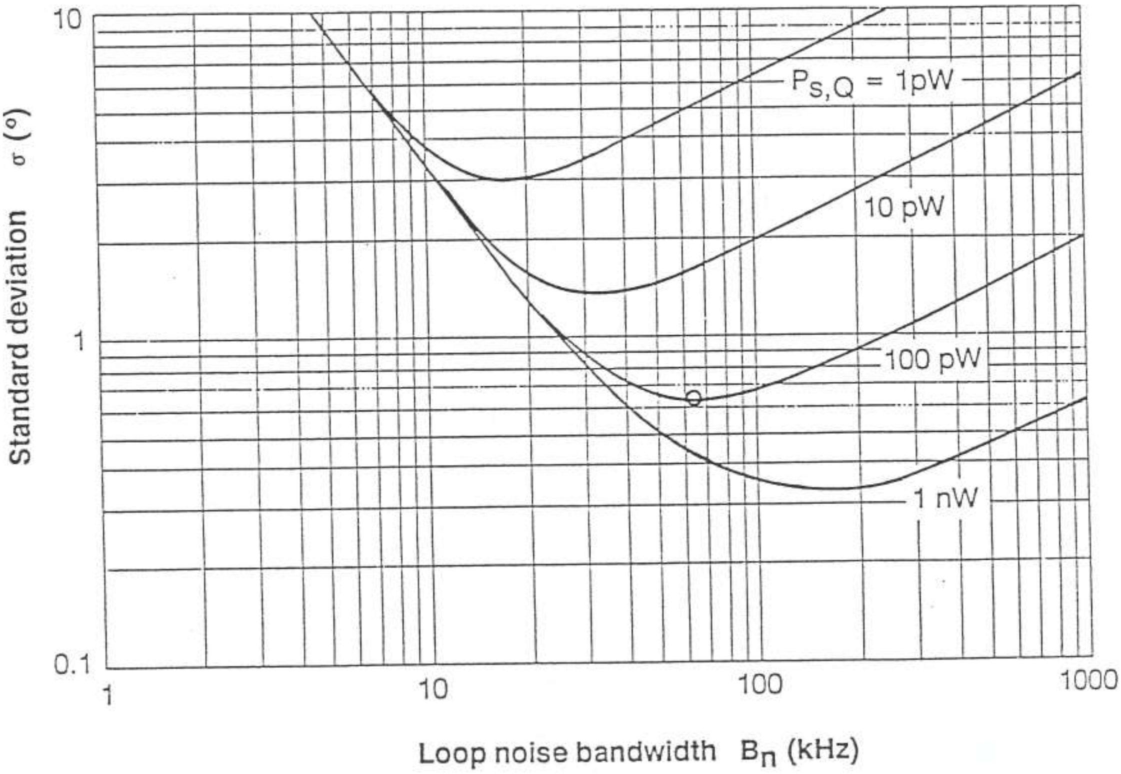


$$S_f = \frac{9.10^7\,Hz^3}{f^2} + \frac{0.34\,Hz}{\pi}$$

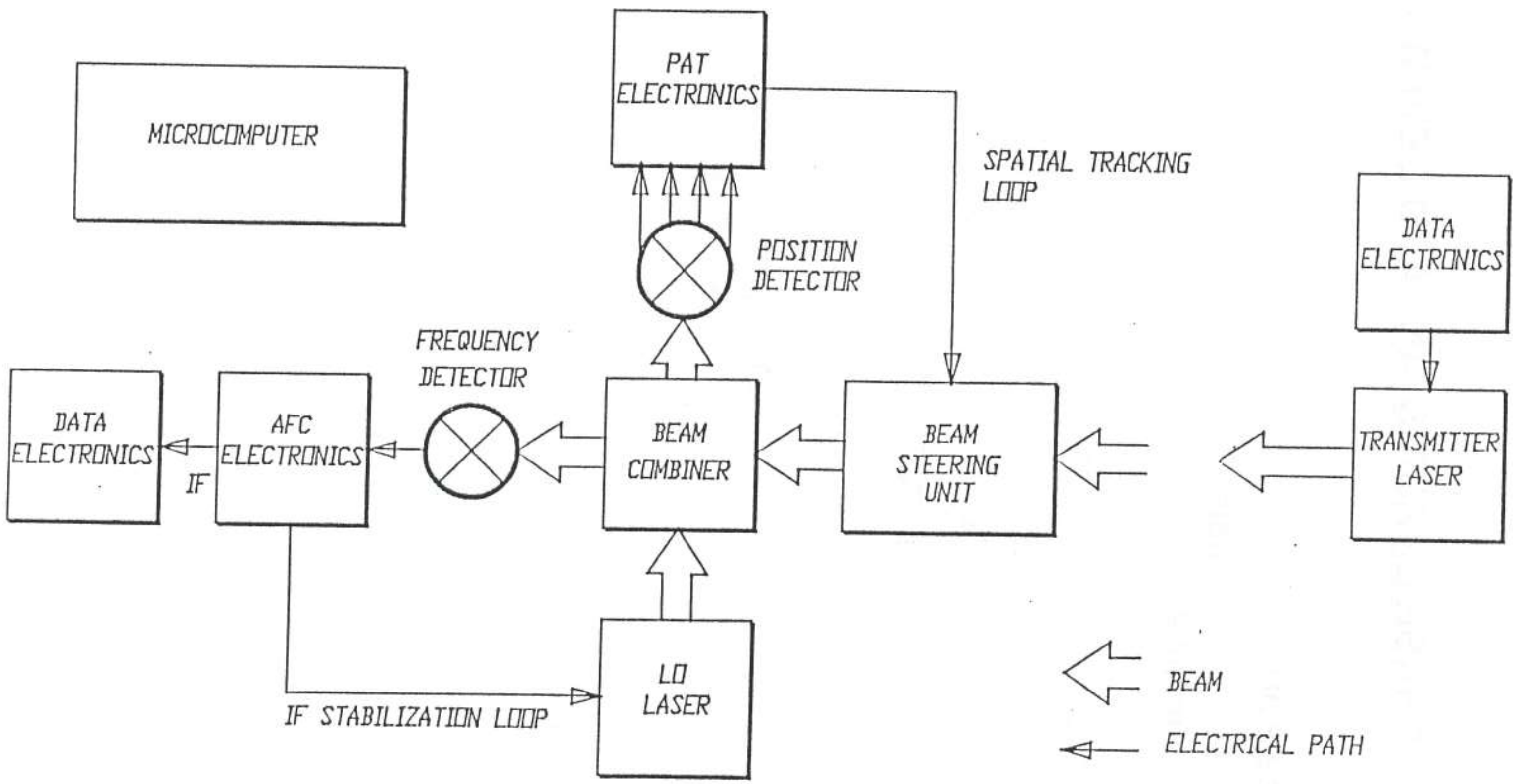
LOOP PHASE ERROR STANDARD DEVIATION

Noise sources

- laser phase noise
- shot noise



HETERODYNE ACQUISITION AND TRACKING LABORATORY MODEL



HETERODYNE ACQUISITION AND TRACKING

LASERS:
- DFB DIODE LASERS
- $\lambda = 1.55\ \mu m$
- $P \approx 2$ mW
- TEMPERATURE- AND CURRENT TUNED
- LINEWIDTH ≈ 12 MHz

INTERMEDIATE FREQUENCY:
- IF = 700 MHz (ACQ AND TR)
- 700 MHz - MARK
  1300 MHz-SPACE } (FSK DATA TRANSMISSION)

PHOTO DIODES:

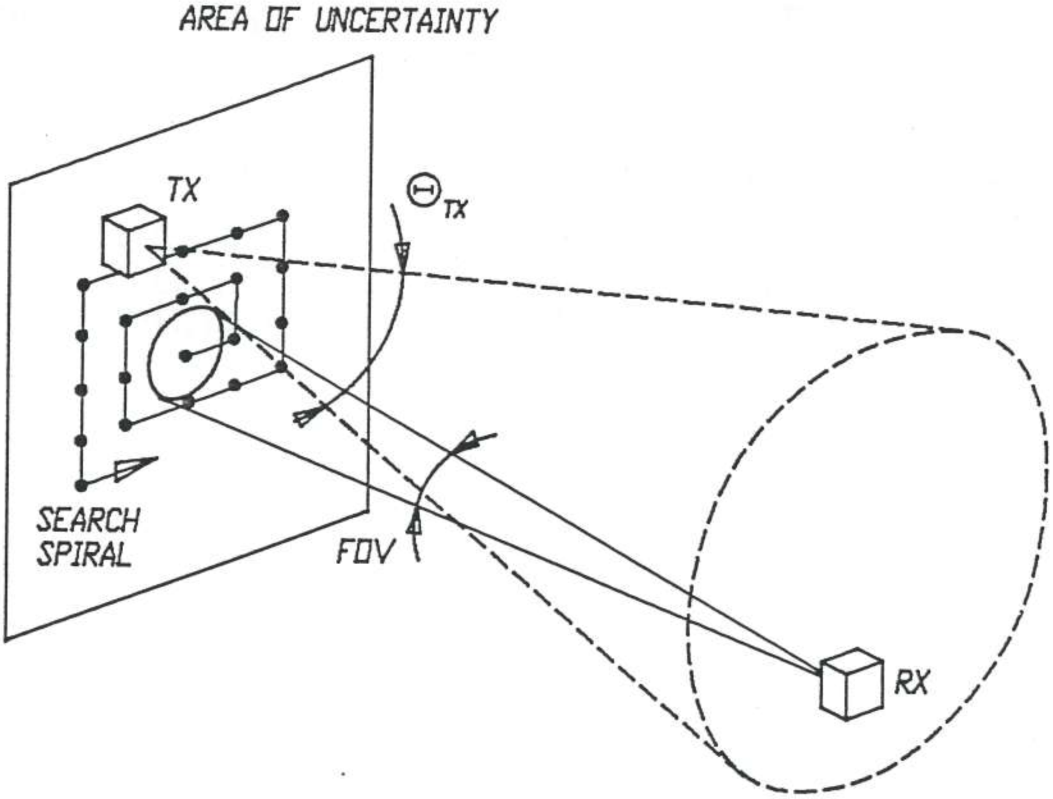
- InGaAs pin

BEAM STEERING:

- 2 GALVANOMETER SCANNERS

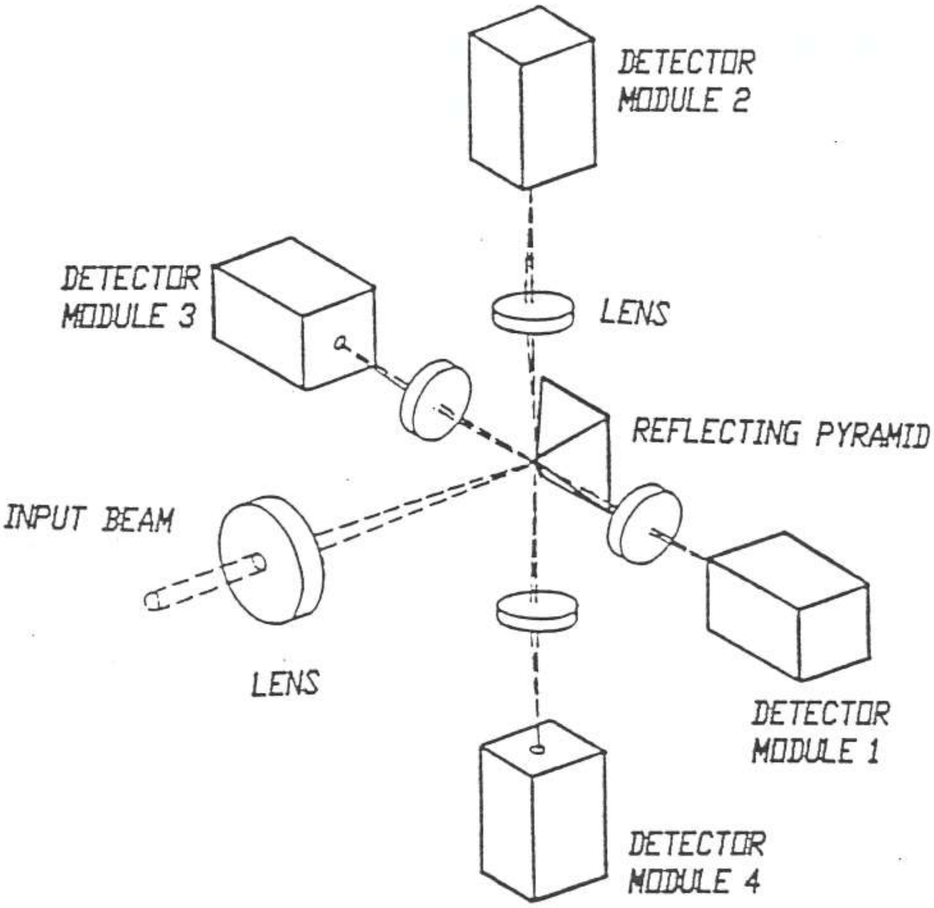
	ACQ	TR
SPATIAL	DIGITAL	DIGITAL
FREQUENCY	DIGITAL	ANALOG

SPATIAL SEARCH STRATEGY

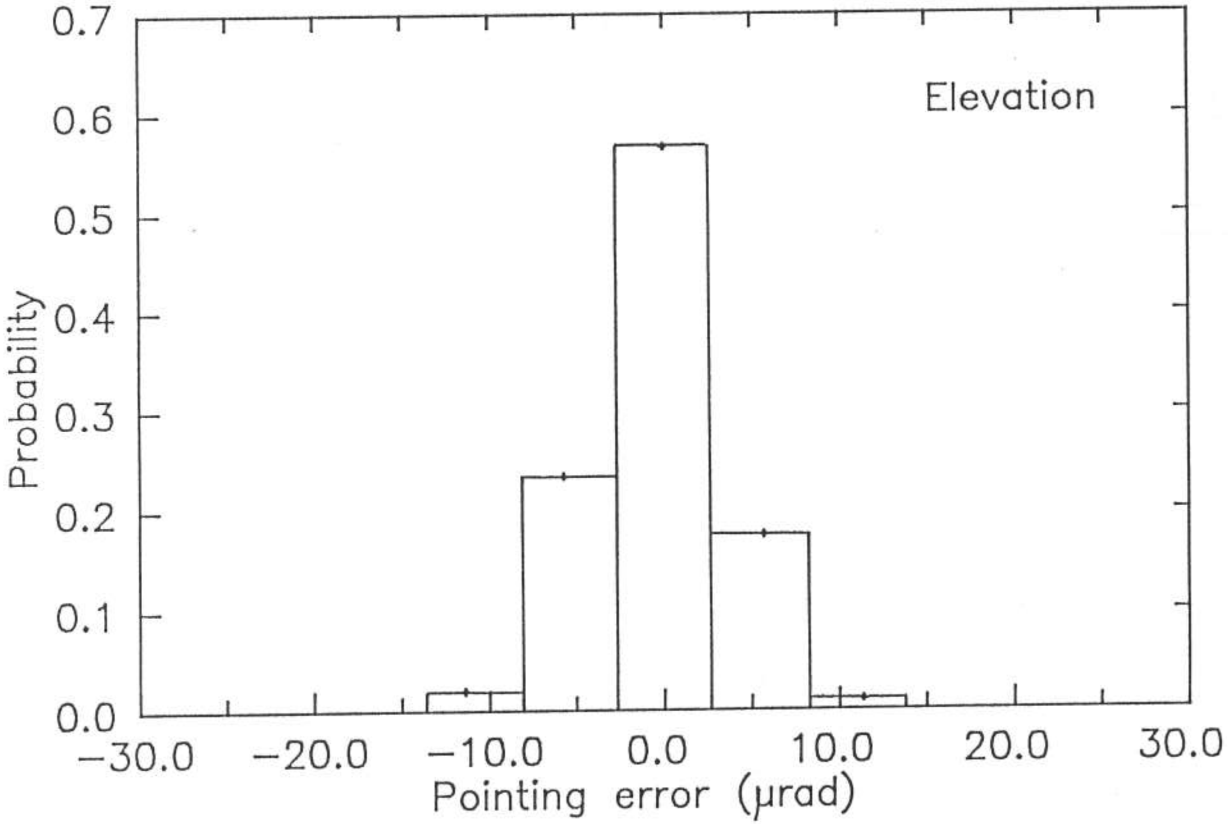


RX ... RECEIVER
FOV ... FIELD OF VIEW
TX ... TRANSMITTER
Θ_{TX} ... TX BEAM DIVERGENCE

HETERODYNE QUADRANT DETECTOR



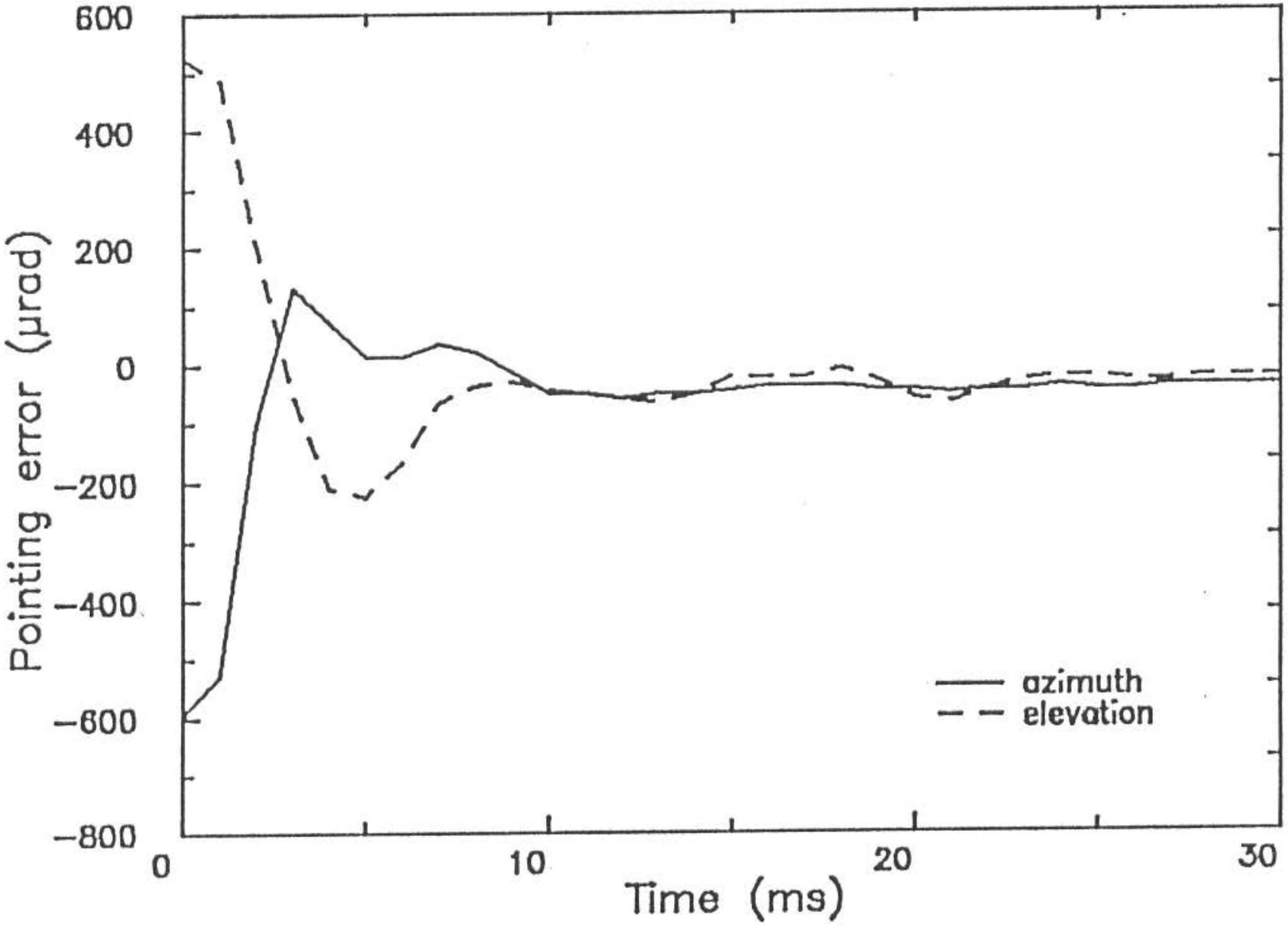
POINTING ERROR DISTRIBUTION



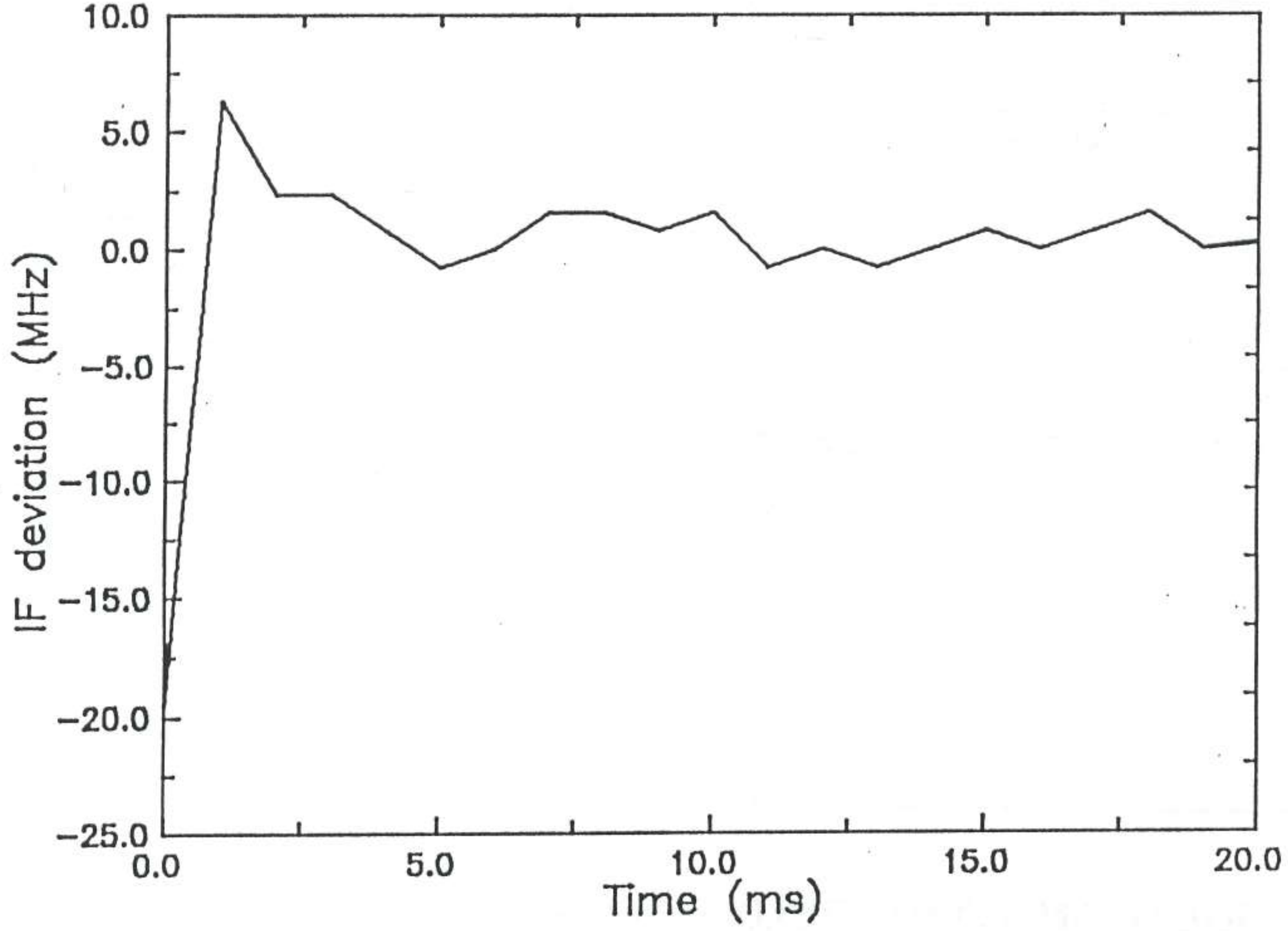
$NEA_{RAD} \approx 6\mu rad$

望鏡遠の倍率で小さく
することができる

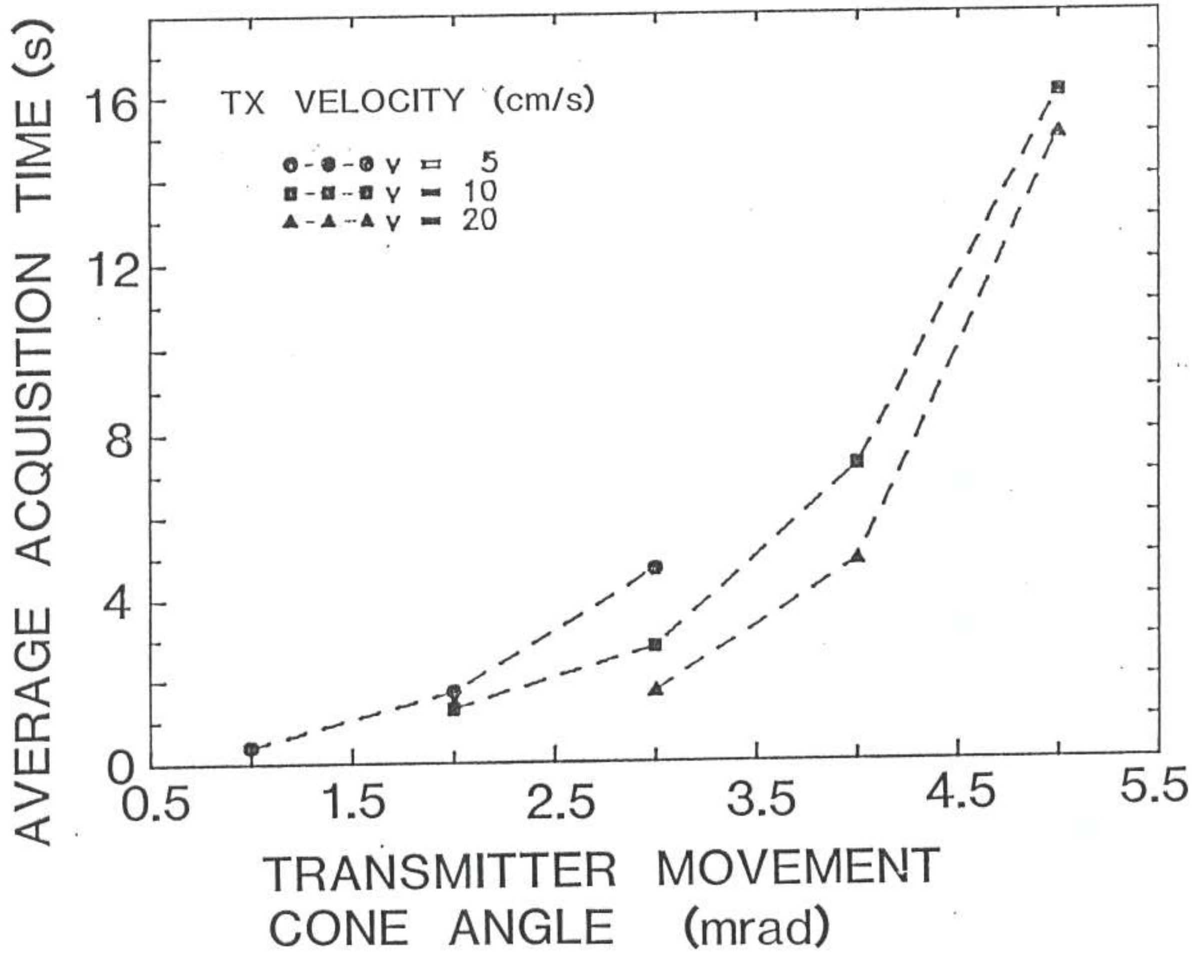
SWITCHING INTO SPATIAL TRACKING MODE



SWITCHING INTO FREQUENCY TRACKING MODE



ACQUISITION TIME



INSTITUT FÜR
NACHRICHTENTECHNIK UND
HOCHFREQUENZTECHNIK

Session 3

Research on Optical Space Communications II

3-1

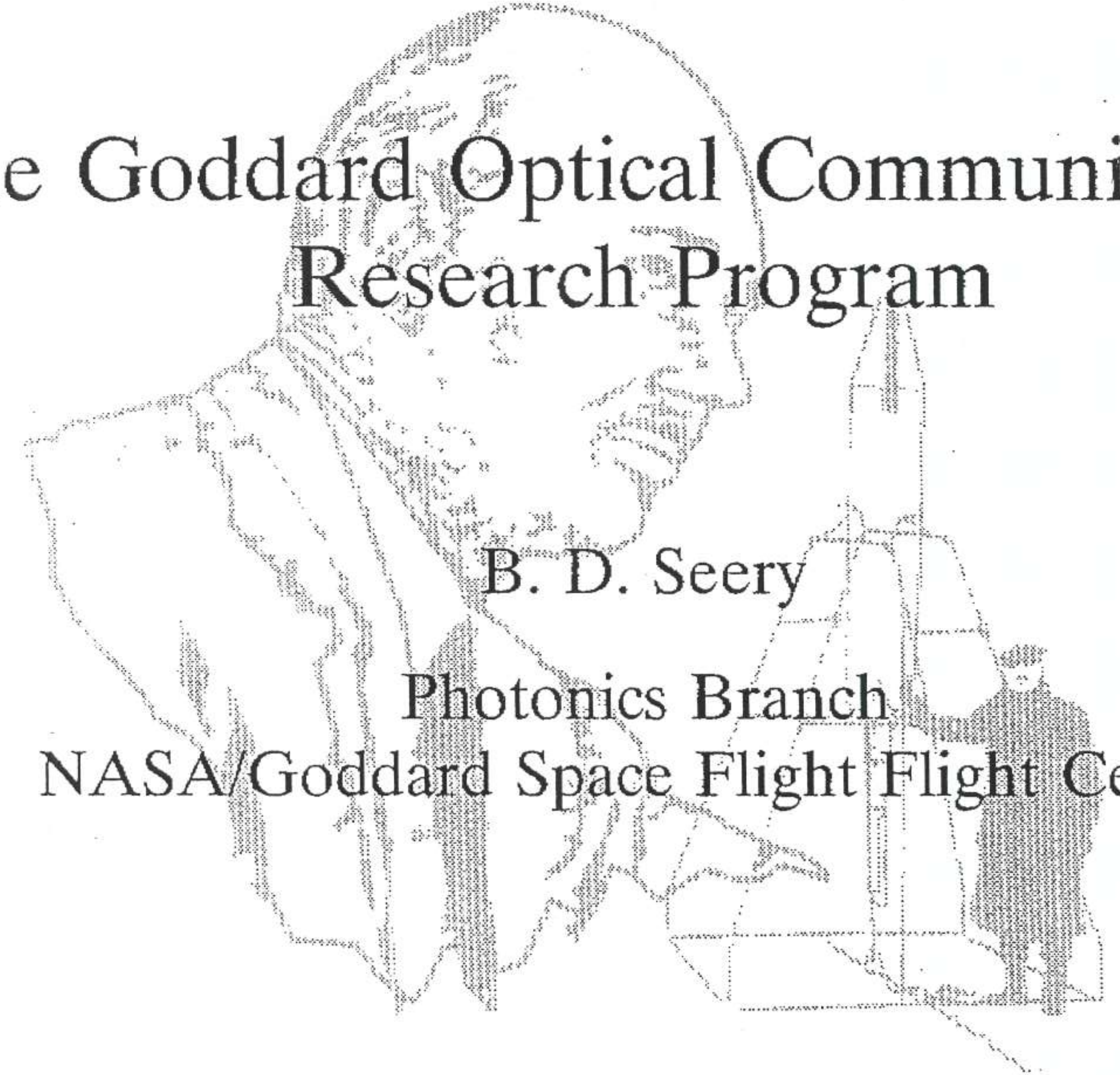
Goddard optical communication research and technology program

Bernard D. Seery

NASA Goddard Space Flight Center

IWOSC '90

December 6 and 7, 1990, ATR, Kyoto



The Goddard Optical Communications Research Program

B. D. Seery

Photonics Branch
NASA/Goddard Space Flight Flight Center

Outline

Objectives:

- High Power Laser Development
  - Single Emitters
  - Arrays
  - MOPA
  - YAG's
- Wideband Modulator Technology
  - Electrical Drivers
  - Optical Modulator
- Noncoherent Power Combining Techniques
  - LPSS
  - Mercene
  - GLBC
- Sensitive Wideband Optical Receivers
  - 220 Mbps Receivers
  - Photoretractive Receiver

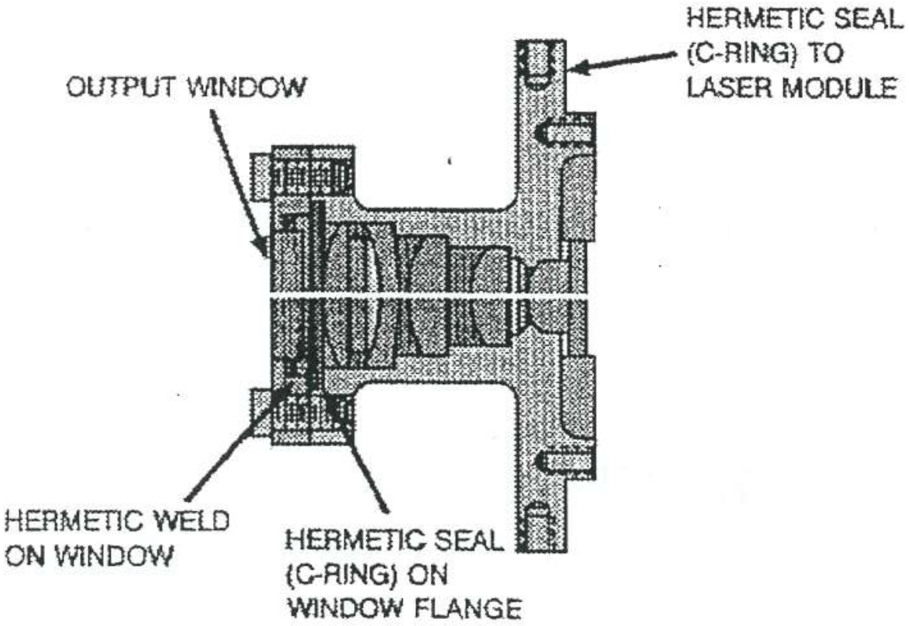
Collaborators

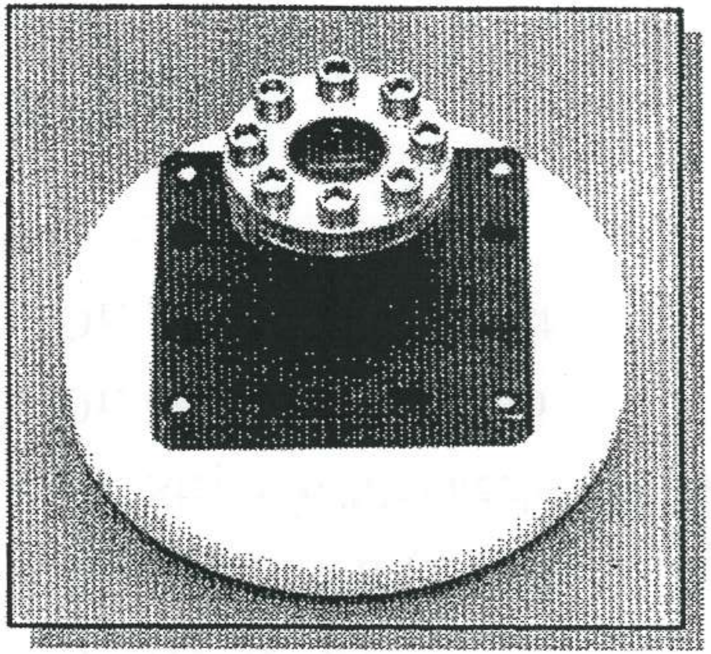
Dr. Michael Krainak, Section Head
Donald Cornwell
Robert Zimmerman
Patricia Mead (U of M)
Prof. Frederick Davidson (JHU)
Paul Spadin
Anna Williams
Prof. Christopher Davis (U ofM)

William Maynard
Glenn Unger
Dr. Babak Saif
Dr. Xiaoli Sun (JHU)
Dr. Stephen Mecherle (TRW)
Dr. Anthony Martino
Dr. Katherine Forrest

A502.012

FLIGHT QUALIFIED LASER COLLIMATOR



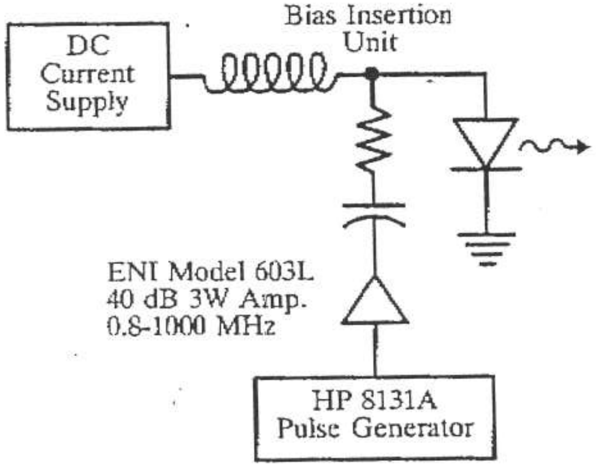


- 5 ELEMENT, SPHERICAL
- FUSED SILICA OPTICS (RAD HARD), INVAR BARREL (THERMAL MATCH)
- MULTI-LAYER DIELECTRIC COATING (99.6% T PER SURFACE)
- LENS ELEMENTS CEMENTED INTO MACHINED SEATS (SHOCK/VIBRATION RESISTANT)
- HERMETICALLY SEALED UNIT (TO PREVENT CONTAMINATION)
- OUTPUT WINDOW WEDGED TO MINIMIZE FEEDBACK TO LASER

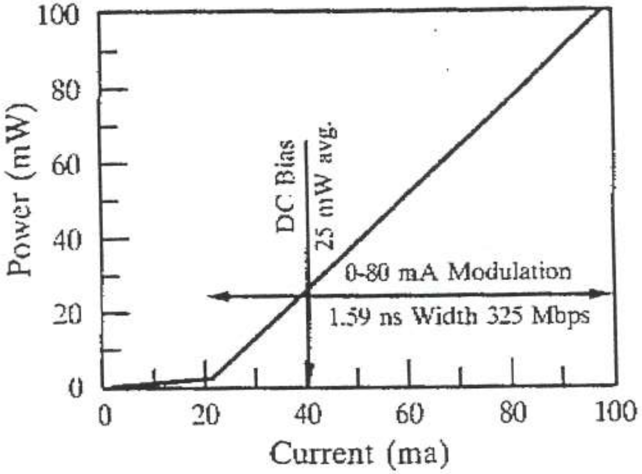
B350.10 BD62

Current Modulation of SDL 5410 Laser Diode

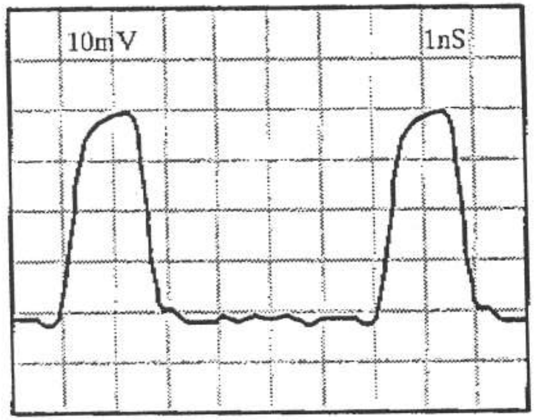
Schematic of Modulation Circuit



Light-Current Relation for 325 Mbps Modulation

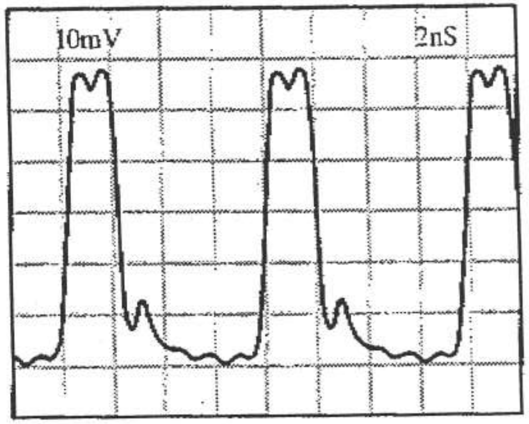


Laser Optical Pulses at 325 Mbps QPPM



Peak Power 100 mW, Average Power 25 mW
Pulse Width = 1.59 nsec, 25% Duty Cycle

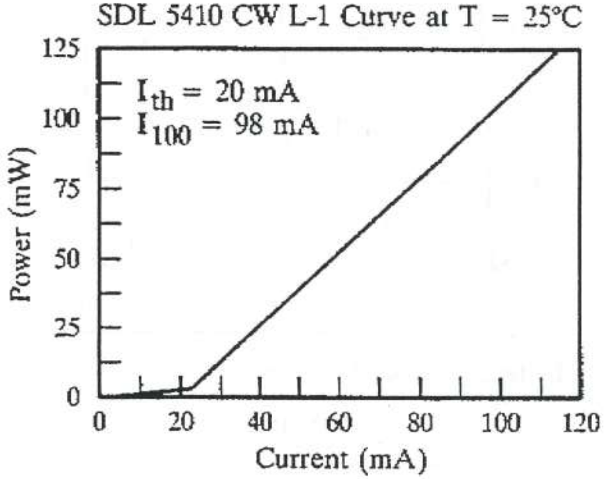
Laser Optical Pulses at 250 Mbps QPPM



Peak Power 400 mW, Average Power 100 mW
Pulse Width = 2 nsec, 25% Duty Cycle

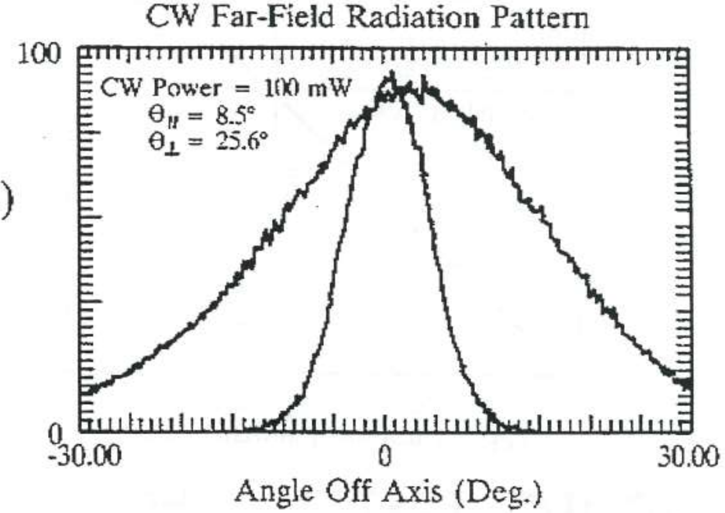
A502.019

Spectra Diode Labs Model 5410 100 mW CW GaAlAs Laser Diode Characterization: L-I and Radiation Pattern Data


SDL 5410 CW L-1 Curve at T = 25°C

Typical Device Characteristics (T = 25°C)

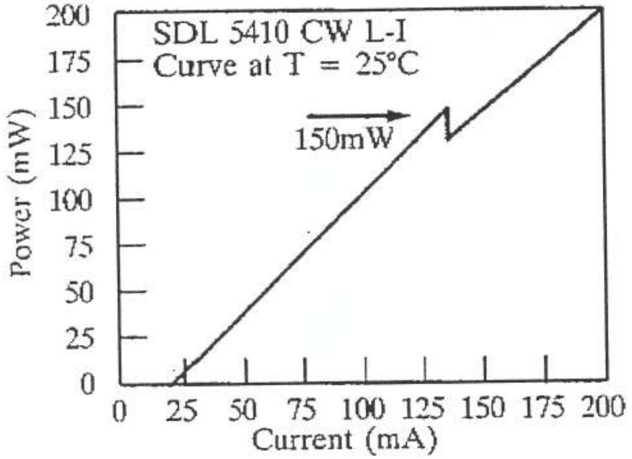
Specific Device Model: SDL-5411-G1
Package Type: SOT-148 Window Package
Wavelength: Typically 820-860 nm
Series Resistance: 4 ohms
Forward Voltage at 100 mW: 2 V
Maximum Reverse Voltage: 3V

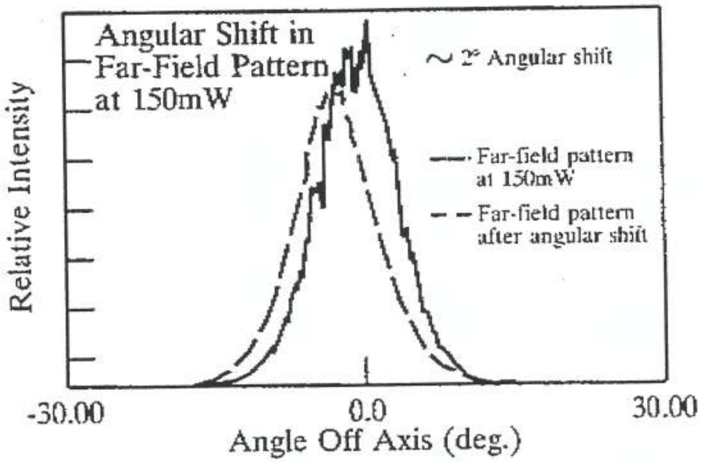

CW Far-Field Radiation Pattern

Key Features:

- Single Quantum Well-
  Separate Confinement Heterostructure (SQW-SCH)
- Single Longitudinal and Transverse Mode up to 140 mW CW Output Power
- 1.3 Optical Watts/Amp, 40% Wallplug Efficiency
- Catastrophic Damage Power Level: 400 mW CW

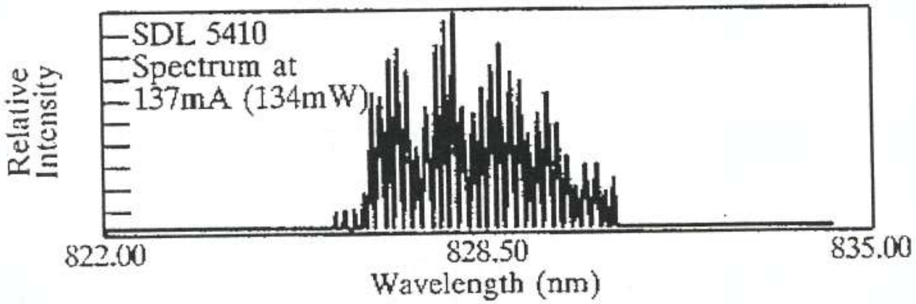
SDL 5410 Behavior at High Power
(>125mW CW)





- Single longitudinal mode operation (831.2 nm) at 135mA (149mW)
- At 137mA bias current:
  - Drop in output power to 134mW ($\Delta P = -15$mW)
  - Discontinuous 2° shift in far-field mode pattern
  - Multi-longitudinal mode operation, with a downward shift in wavelength

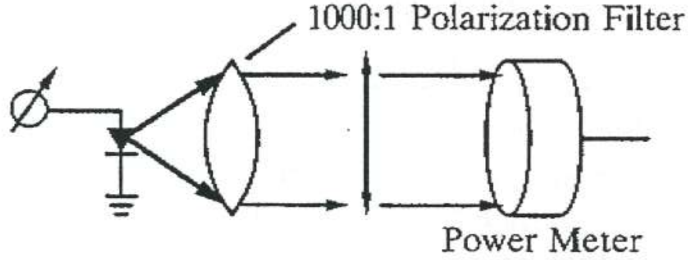
➡ Discontinuity in power, far-field, and spectrum believed due to spatial hole burning



SDL 5410 Polarization Ratio versus Drive Current

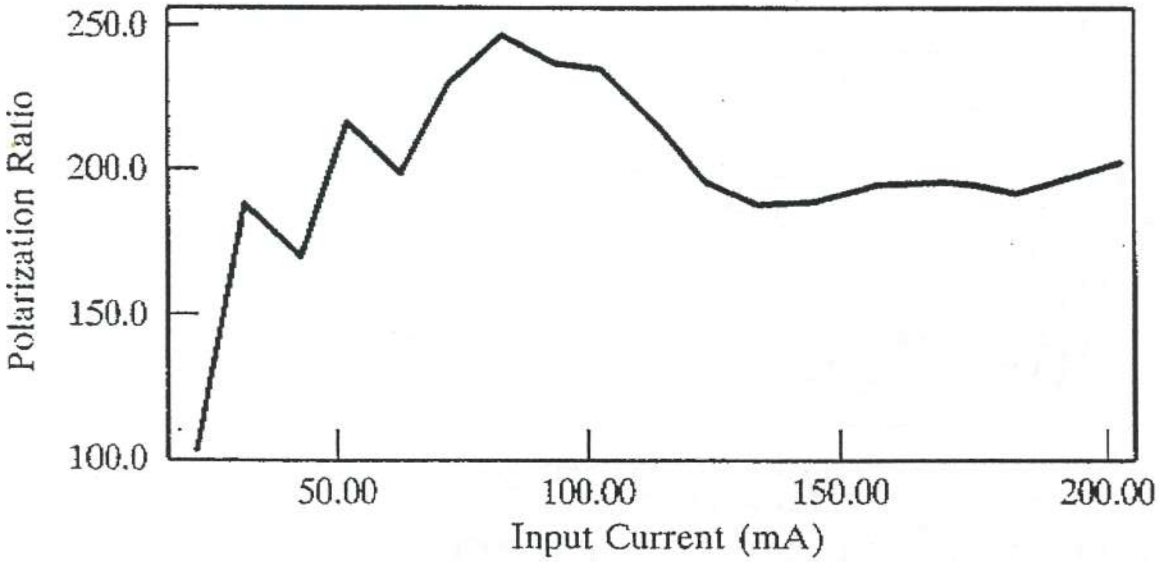
- Polarization ratio is a measure of stimulated emission versus spontaneous emission, and therefore an indicator of the lasing power of the device versus the spontaneous noise

Test Set-Up:



Modulated Polarization Ratio: 180:1

at 400mW peak power, 100mW average power, 250 Mbps QPPM



A502.018

GSFC

SDL 5410 Far-Field Pattern Behavior versus Power

CW $\Delta\theta/\Delta P$ Before 150 mW:
0.0035°/mW
0.04% Beamwidth/mW

Modulated $\Delta\theta/\Delta P$ Before 150 mW:
0.0025°/mW
0.03% Beamwidth/mW

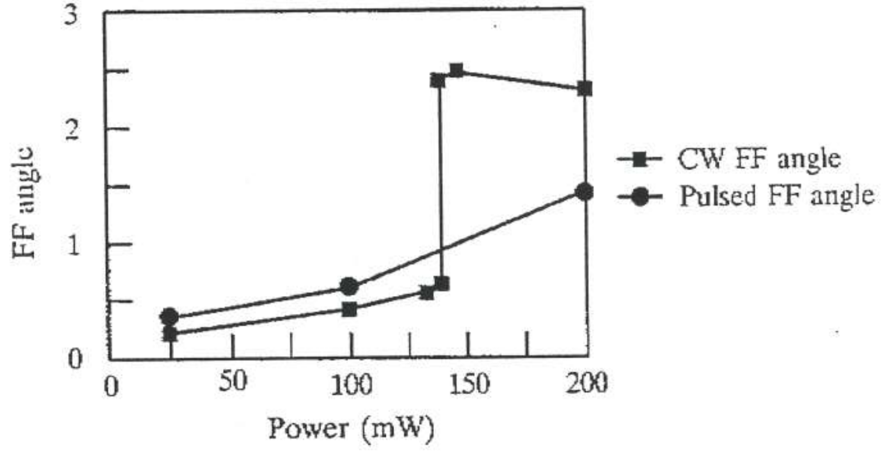
CW Δ(Width)*/ΔP Before 150 mW:
0.00086°/mW
+0.01% Beamwidth/mW

Modulated Δ(Width)*/ΔP Before 150 mW:
0.0035°/mW
+0.04% Beamwidth/mW

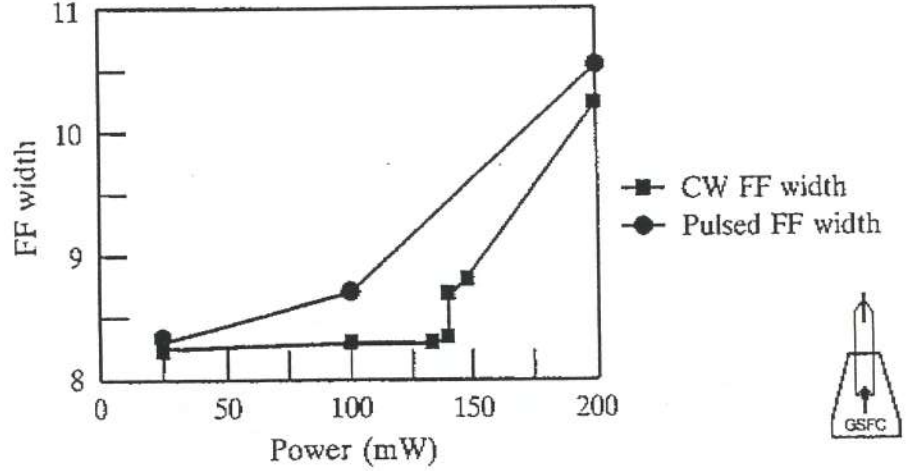
*Far-Field = FWHM
Results Submitted to Applied Optics,
December 1990

A502.017

SDL AD323 CW and Pulsed FF Angle vs. Power

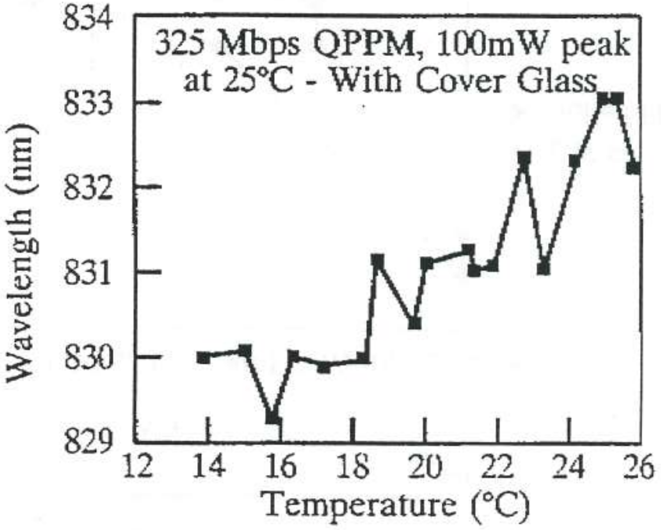


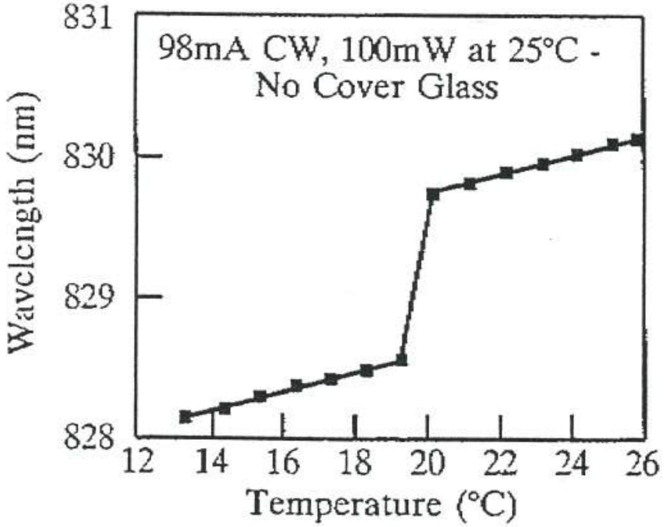
SDL AD323 CW and Pulsed FF Width vs. Power

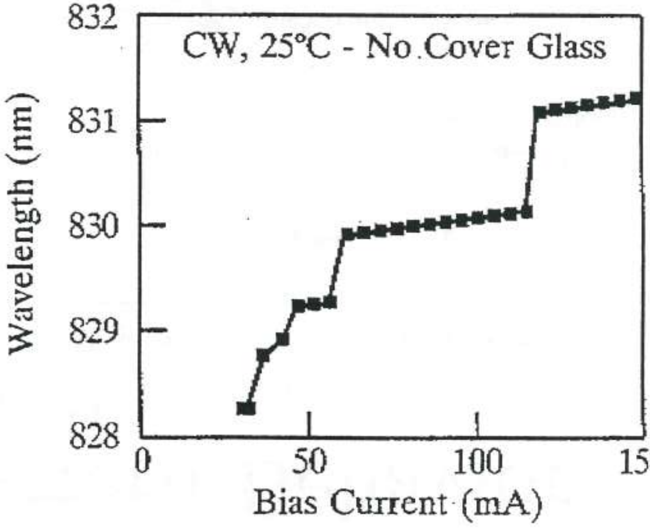


SDL Model 5410-G1 Laser Diode, #AD323

- Mode hops of ~ 0.8 nm observed when the laser diode output is modulated
- Consistent with a 0.3 nm thick cover glass acting as an external etalon
- Broad regions of single mode lasing, CW, versus both temperature and current



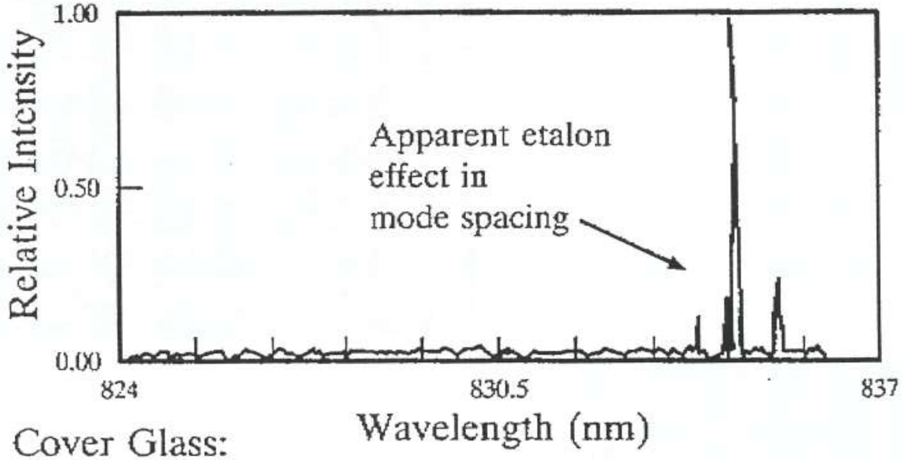




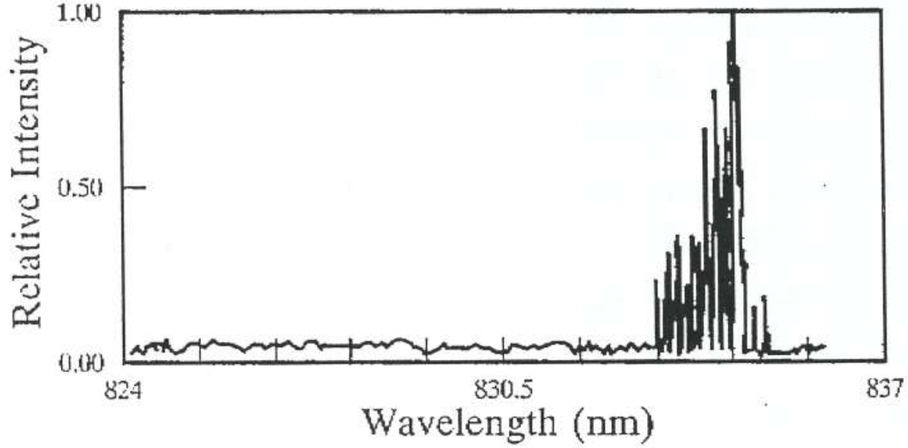
A502.016

SDL Model 5410-G1, #AO323:
250 Mbps QPPM, 23°C, 400mW Peak, 100mW Avg.

With Cover Glass Present:



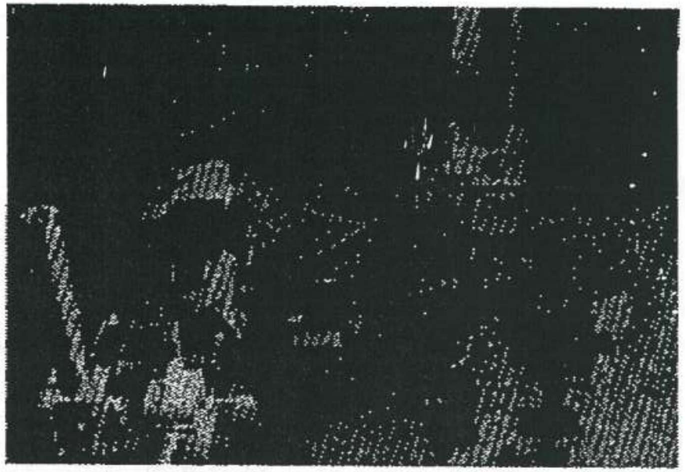
Without Cover Glass:

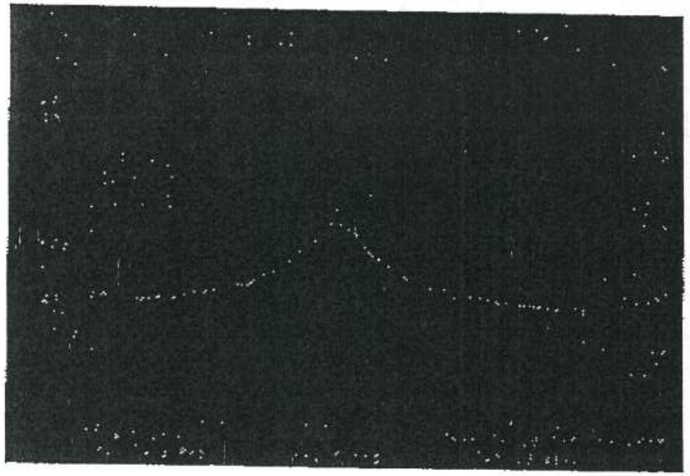


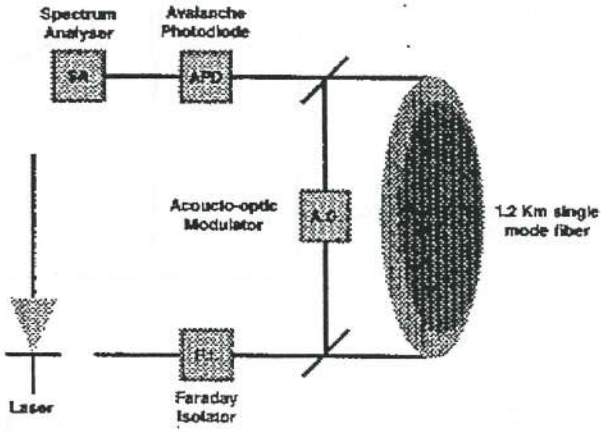
* Cover glass appears to reinforce single longitudinal mode oscillation

Fiber Self Heterodyne Interferometer

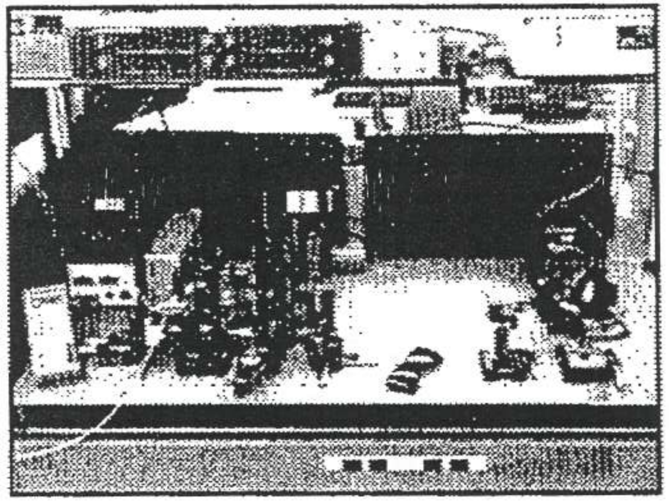
- 100 KHz linewidth resolution
- Frequency chirp measurements under intensity modulation

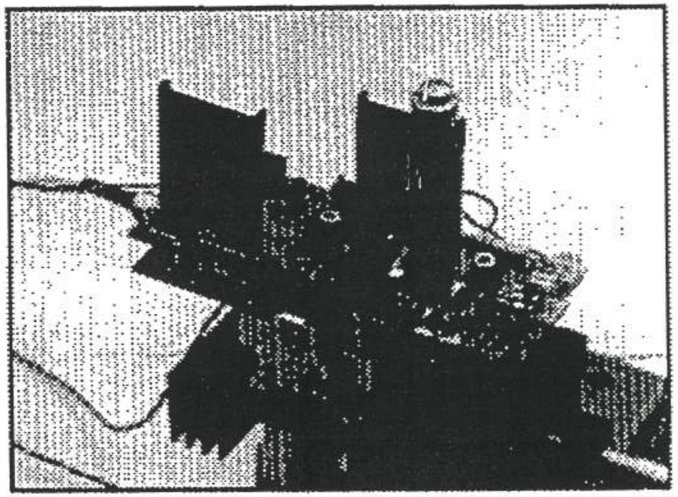




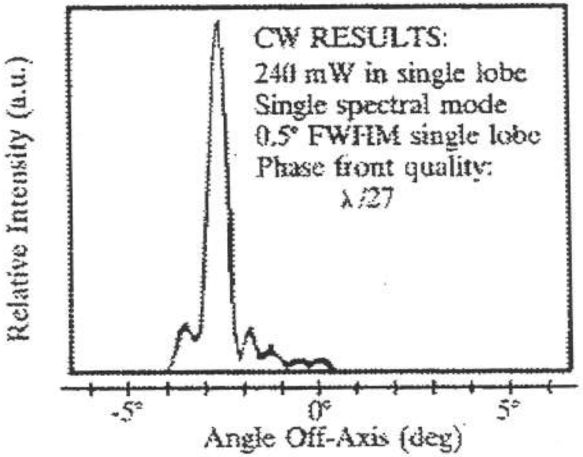


External Control of High-Power Semiconductor Lasers: Injection-Locking of AlGaAs Arrays



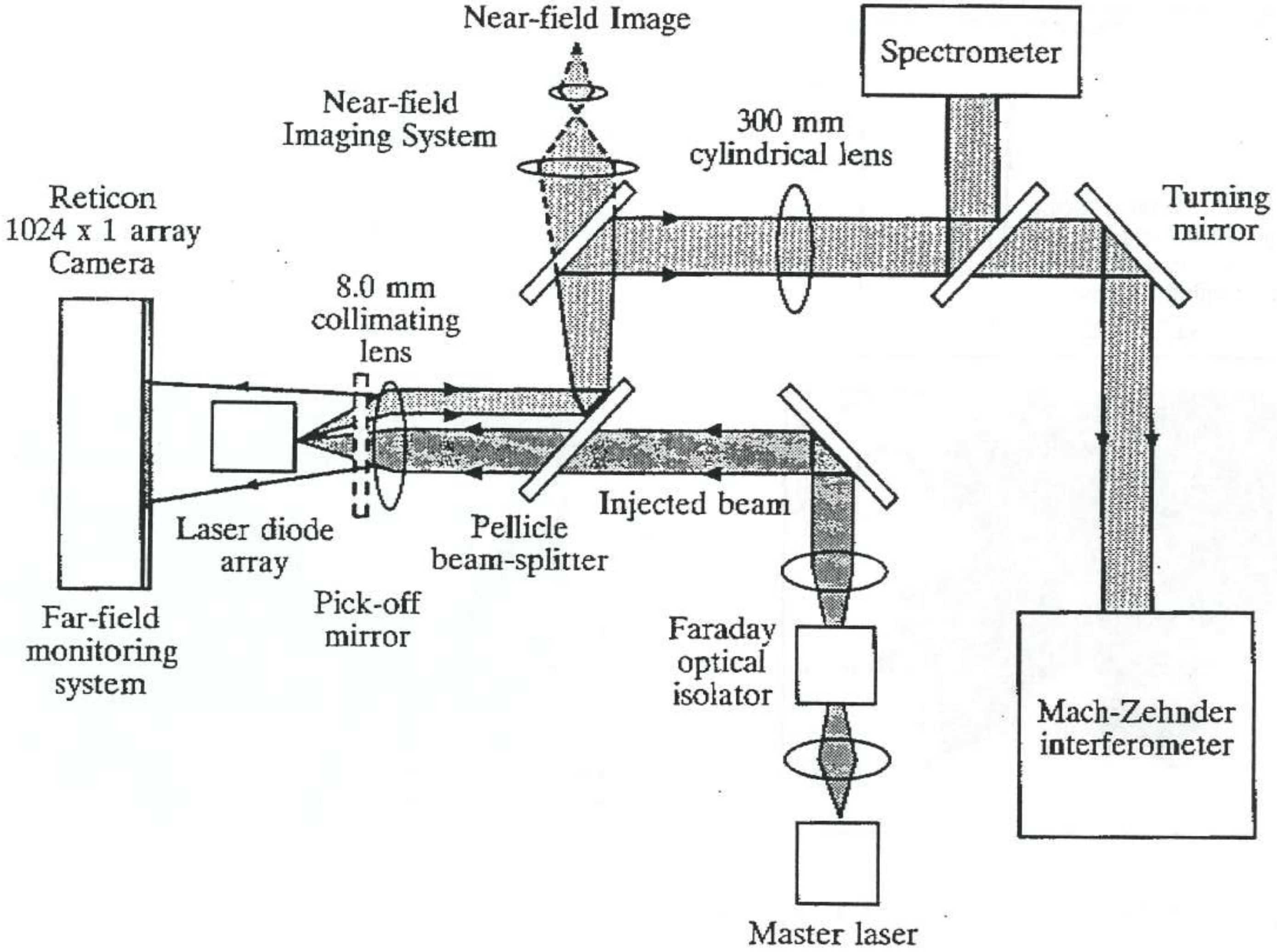


- FEATURES
- 240 mW diffraction-limited CW output, single longitudinal mode
- 240 mW peak power in single far-field lobe at 50 Mbits/sec NRZ



A502.23 BD68

Injection-Locking Configuration



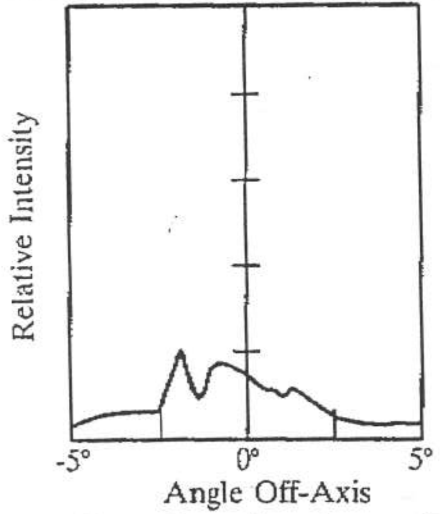
A404.007

Injection-Locked, Current-Modulated Laser Array

Total Array Output Power: 270 pk
135 avg.

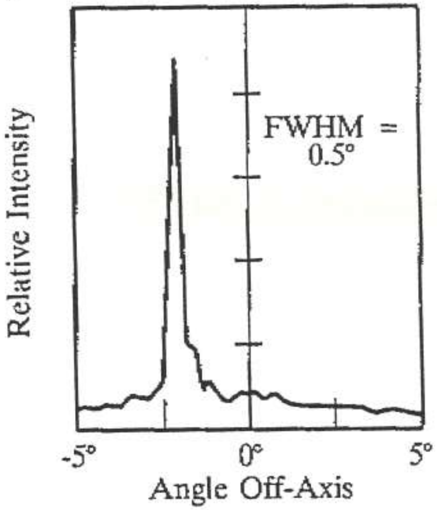
Modulation: 25 MHz 50% duty cycle, 50 Mbits/sec NRZ
Single-Lobe Power: 216mW peak, 108mW average

Free-Running Array Far-Field

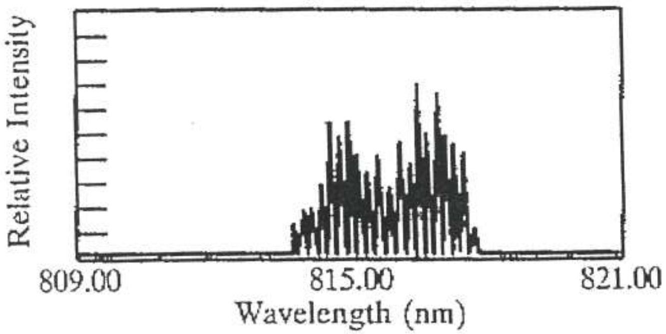


Locking Bandwidth:
0.63 Å or
27 GHz
Injected Power: 6mW
Angular Steering Range: 1.0°
Angular Tuning Rate:
3.7 x 10^{-2} deg/GHz

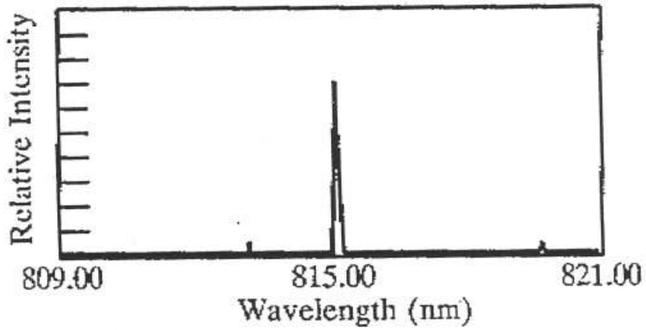
Injection-Locked Array Far-Field



Free-Running Array Spectrum



Injection-Locked Array Spectrum

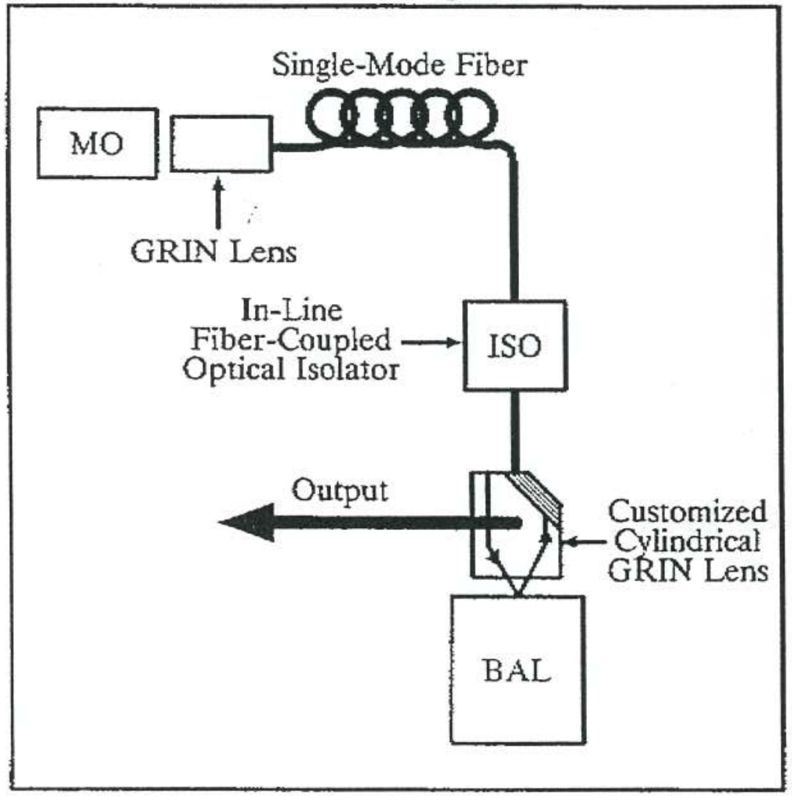


A502.022

Fiber-Coupled Injected Broad Area Laser Amplifier

(University of Maryland, College Park)

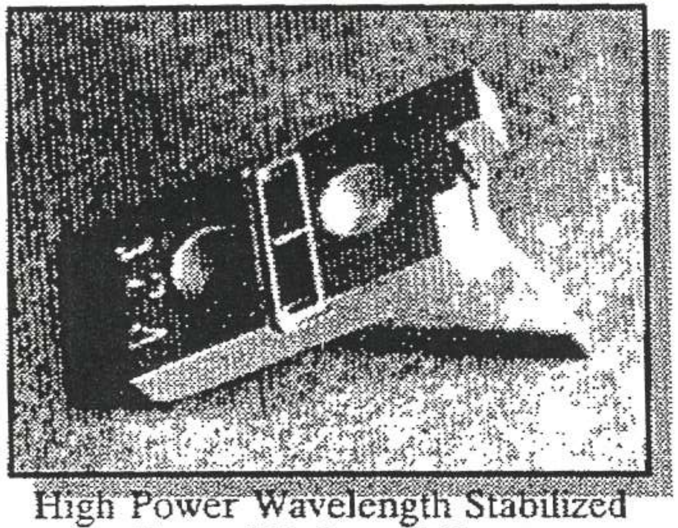
System Configuration



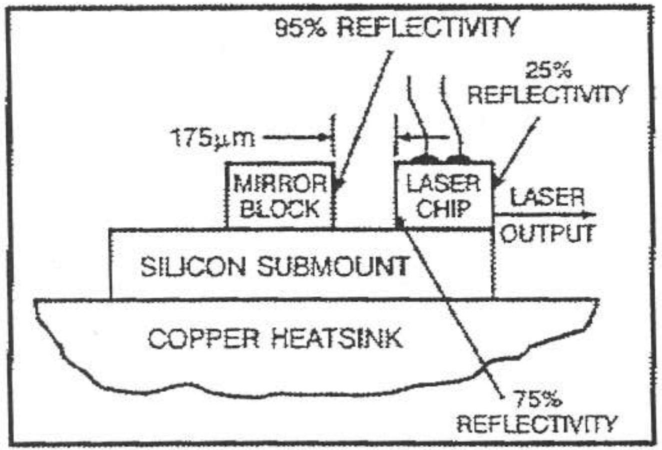
Key Features:

- Based on Fabry-Perot amplifier model of BAL (Abbas, et. al., 1988). Requires 200μm x 1μm injected spot
- Amplifier is 400μm broad area laser with multiple quantum well (MQW) structure for reduced gain saturation
- Uses customized "cylindrical" GRIN lens to form required injected spot size
- Master oscillator is 30mW single-mode, single-stripe diode laser
- Ideal output 500mW in a single far-field lobe, single longitudinal mode

Flight Qualified Laser Technology



High Power Wavelength Stabilized Laser Diode at 860nm

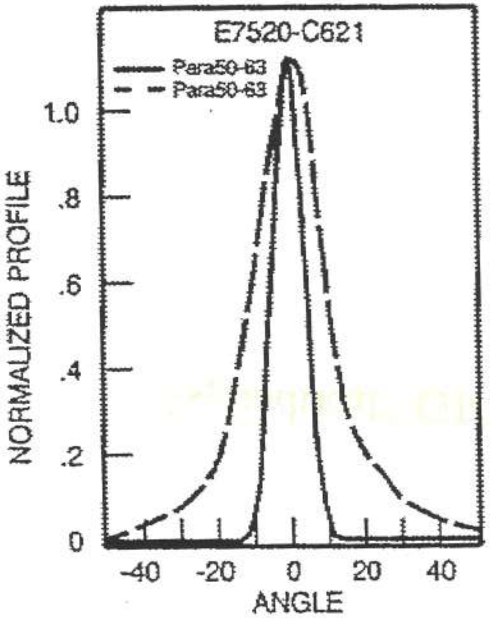


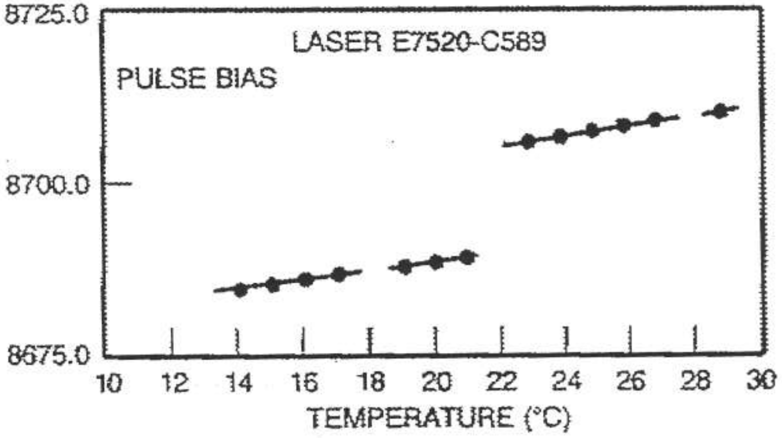
Third Mirror on Chip

A502.24 BD68

Lasing Spectrum at 63mW

50% Duty Cycle

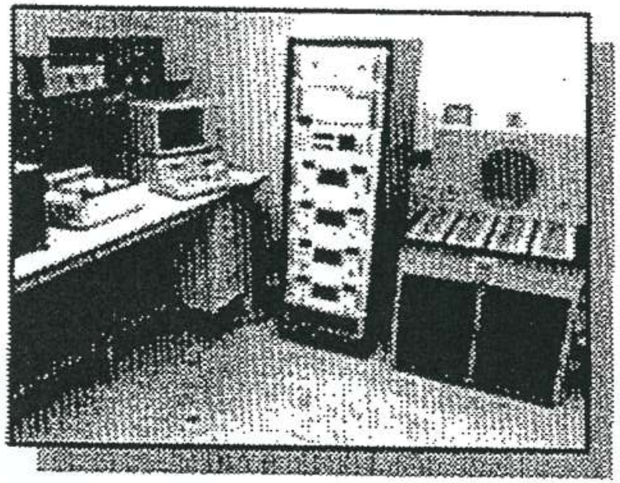




Ref.

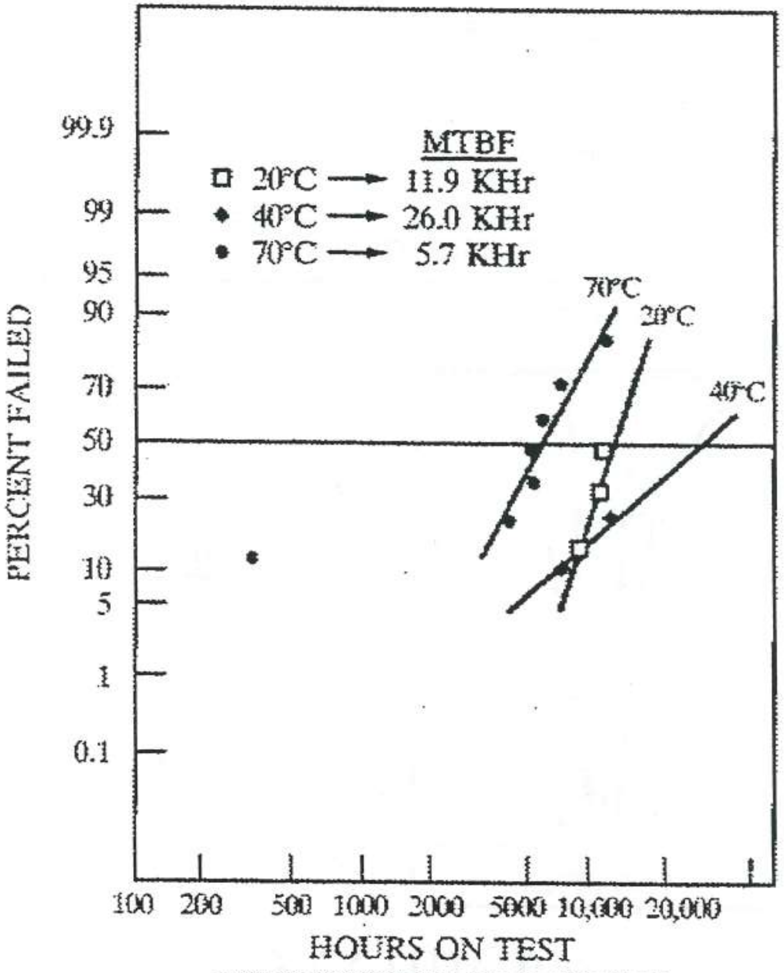
BTRS 70mW Lifetest Results

Diode Lifetest Facility



Test Conditions:

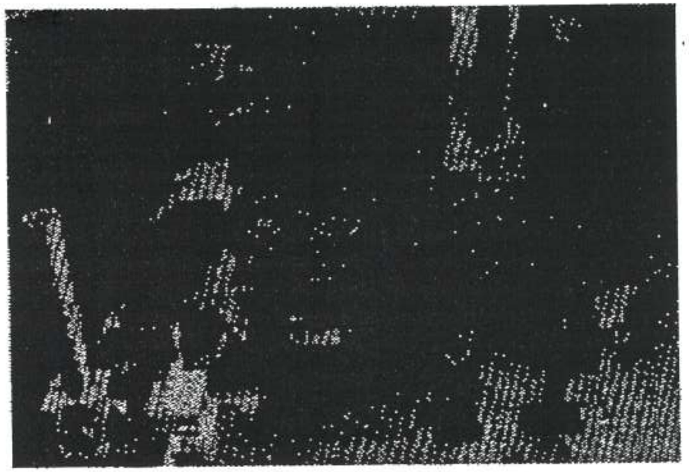
- Sample Population
  - 8 Lasers at 70°C
  - 8 Lasers at 40°C
  - 8 Lasers at 20°C
- 10 MHz Modulation
- Constant Optical Power

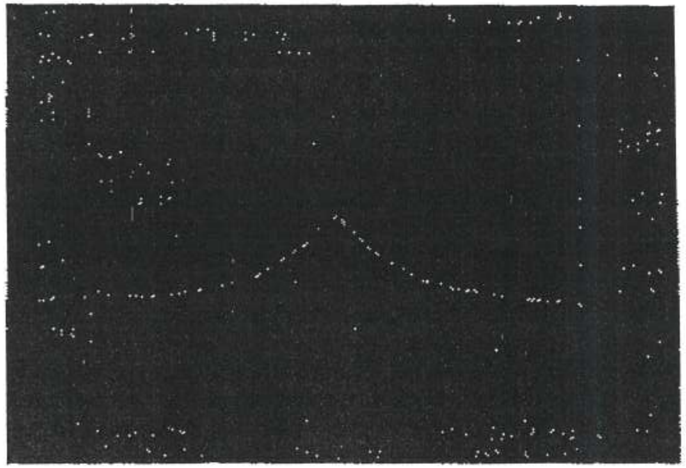


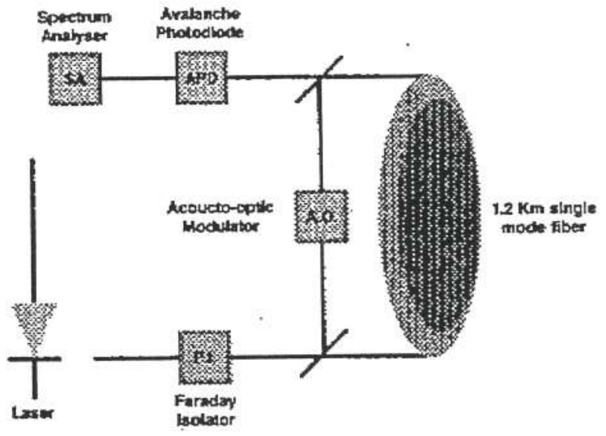
DISTRIBUTION OF FAILURE

Fiber Self Heterodyne Interferometer

- 100 KHz linewidth resolution
- Frequency chirp measurements under intensity modulation



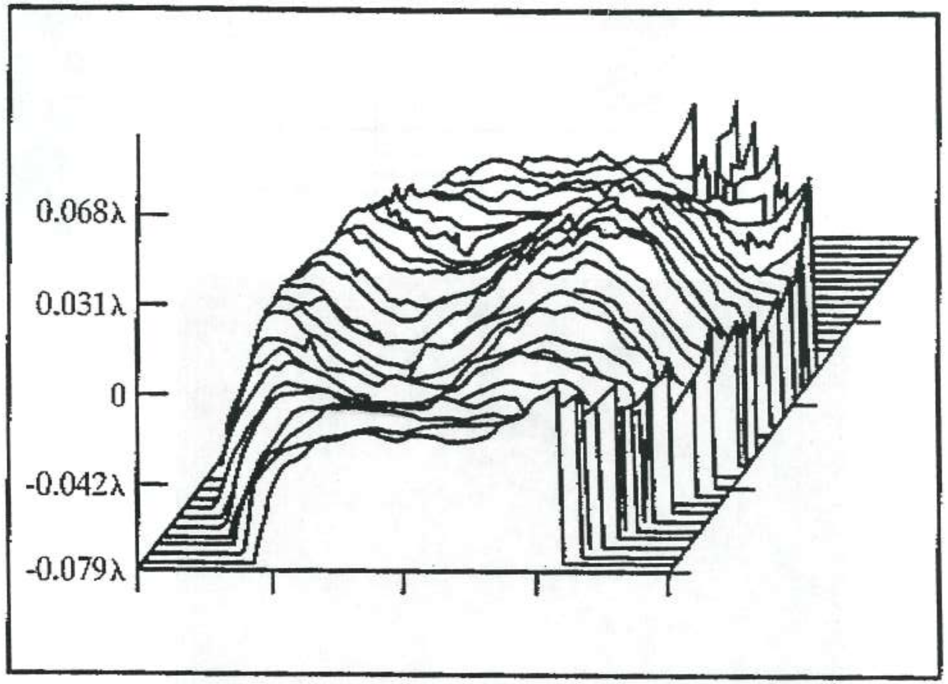




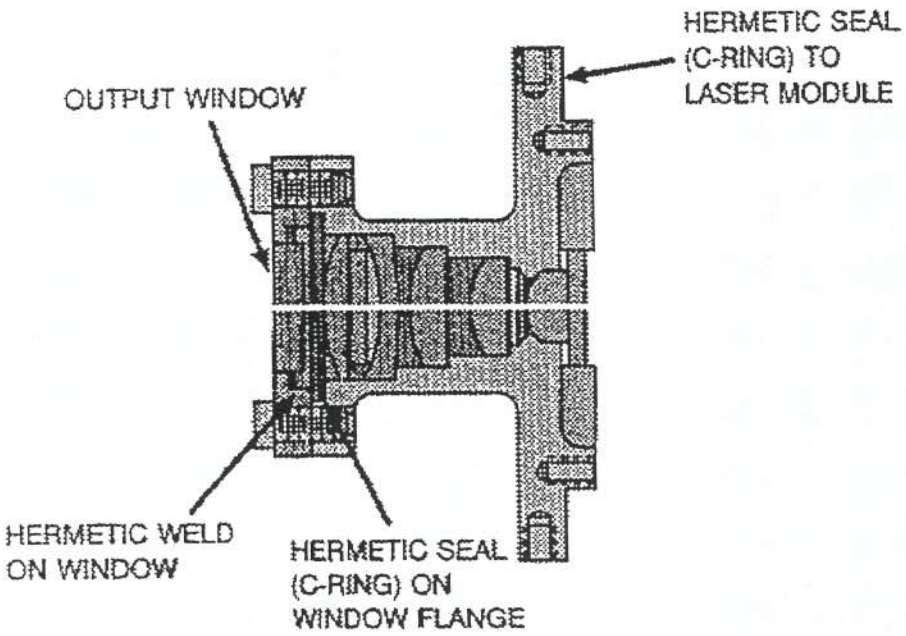
L403L.009

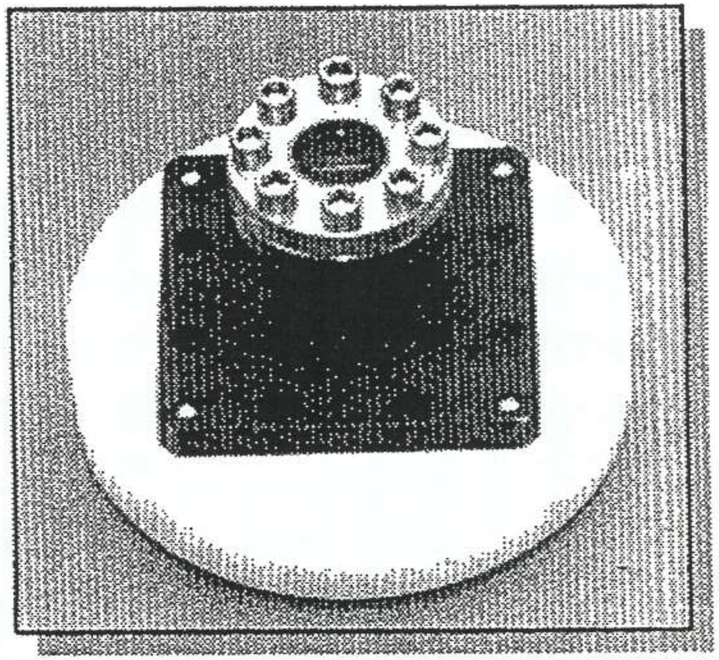
Flight Qualified Laser Collimator
(TRW, Inc.)

- Temperature Range
  - 40 to + 70°C (Storage)
  + 4 to + 24°C (Operating)
- Wavefront Error
  $\lambda/40$ RMS
  ± 1 Degree Field of View
- Transmission
  $> 95\%$
  863 - 874 mm
- Hermetic Seal
  $< 5 \text{ X } 1^{-7}$ ATM cc/sec Helium


OPD Contour Plot

FLIGHT QUALIFIED LASER COLLIMATOR





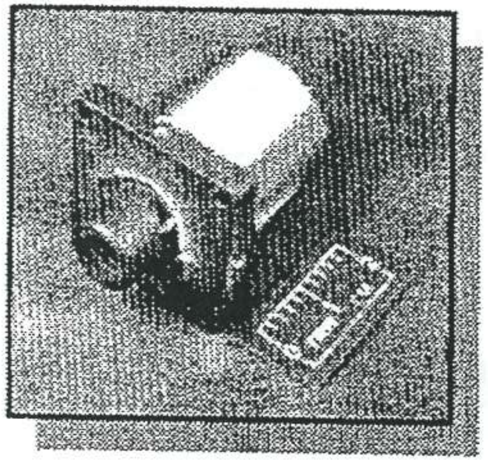
- 5 ELEMENT, SPHERICAL
- FUSED SILICA OPTICS (RAD HARD), INVAR BARREL (THERMAL MATCH)
- MULTI-LAYER DIELECTRIC COATING (99.6% T PER SURFACE)
- LENS ELEMENTS CEMENTED INTO MACHINED SEATS (SHOCK/VIBRATION RESISTANT)
- HERMETICALLY SEALED UNIT (TO PREVENT CONTAMINATION)
- OUTPUT WINDOW WEDGED TO MINIMIZE FEEDBACK TO LASER

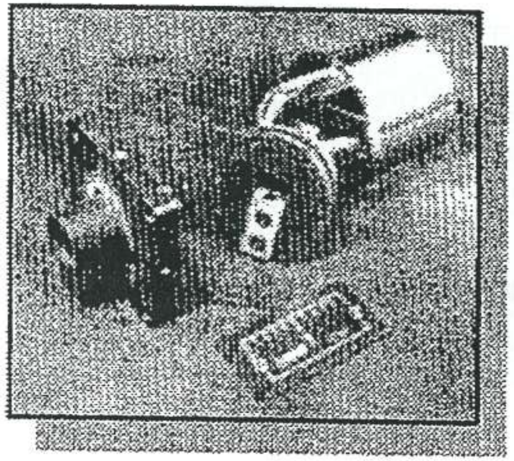
B350.10 BD62

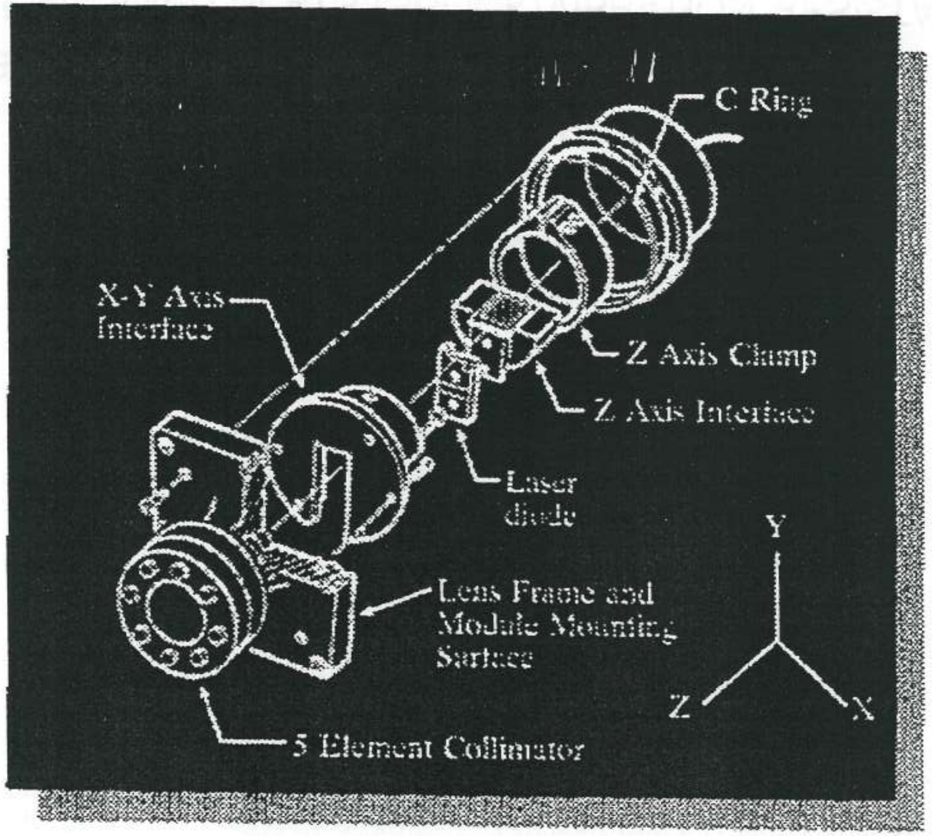
6 in the unit

Laser Transmitter Module

(TRW, Inc.)







A502.06 BD68

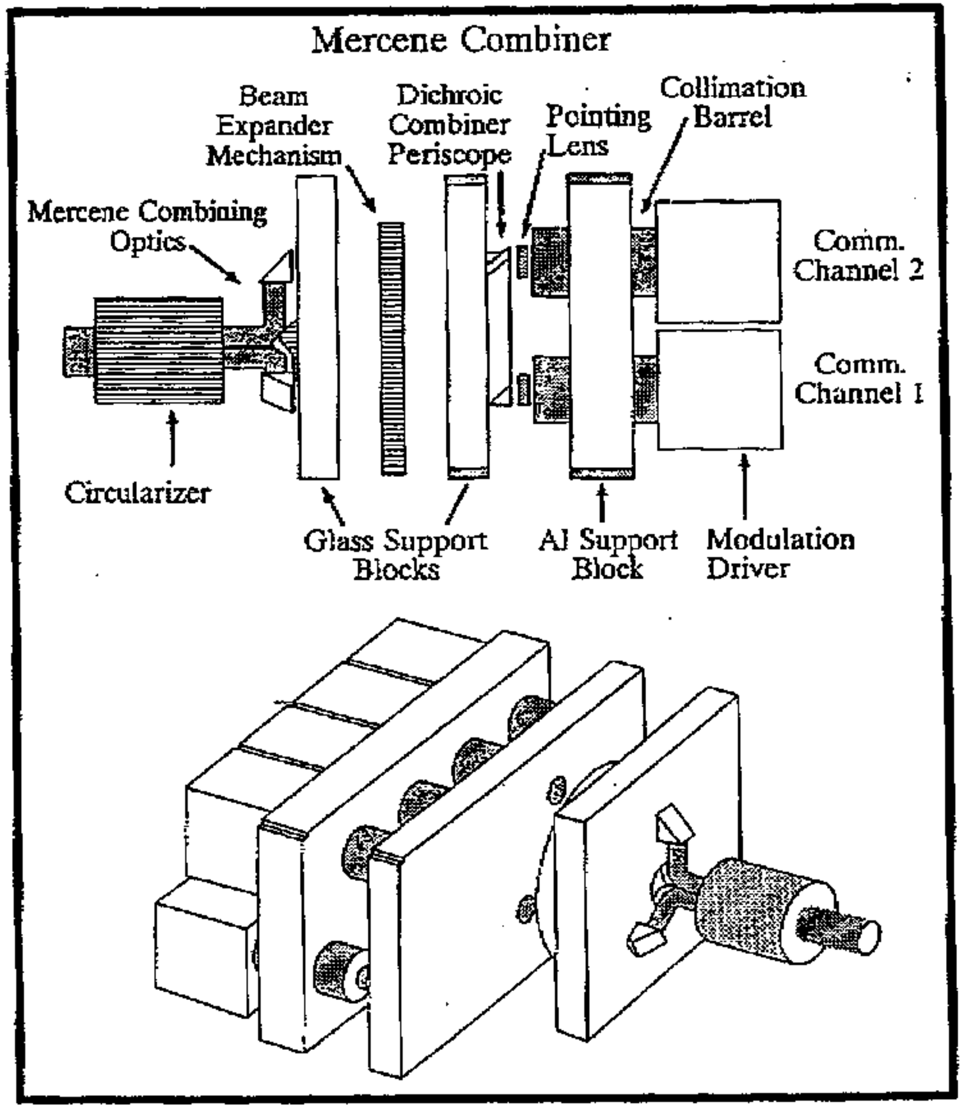
High Power Diode Laser Spatial Combiner

Requirements:

- Individual Lasers Collimated to ≤1.2 x Diffraction Limit
- λ /30 rms Wavefront Quality
- ±20 microradian beam pointing stability
- 325 Mbps Data Rate per Channel

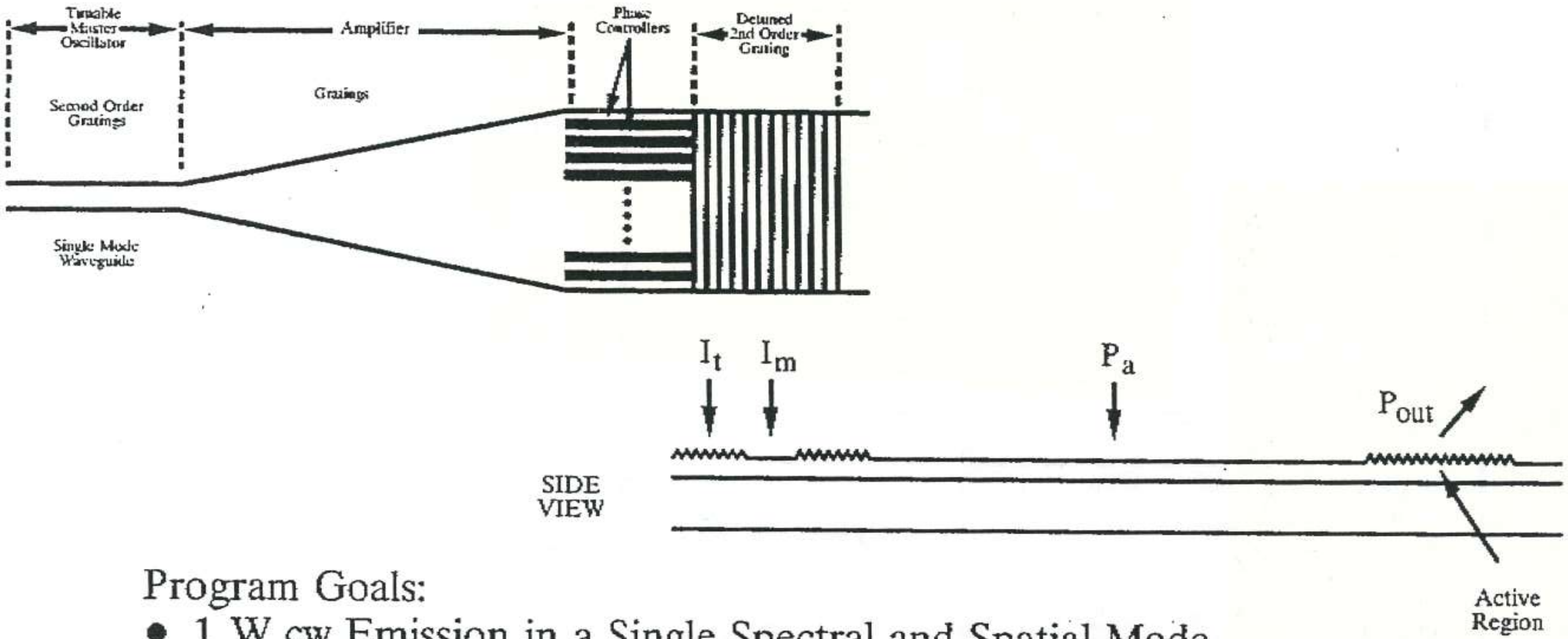
Features:

- Combination of Dichroic and Spatial Combining
- SDL 5410 Series Laser Diodes Operating at 200mW Peak
- Broader Beamwidths Reduce Pointing Accuracy Requirements



A502.003

One Watt Monolithic Master Oscillator Power Amplifier



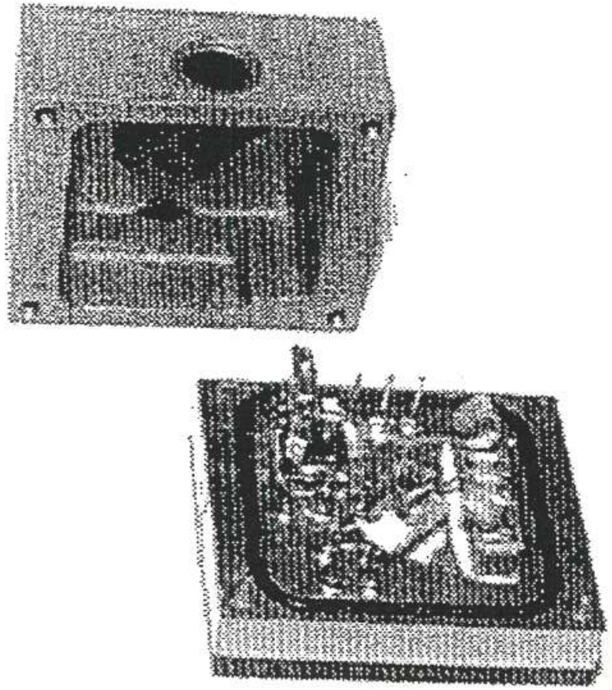
Program Goals:
- 1 W cw Emission in a Single Spectral and Spatial Mode
- 0.5 GHz Modulation Bandwidth

- Master Oscillator Tunable Over a 5 nm Emission
- Range Coupled to the Flared Wavelength MOPA Operating at Low Output Powers.

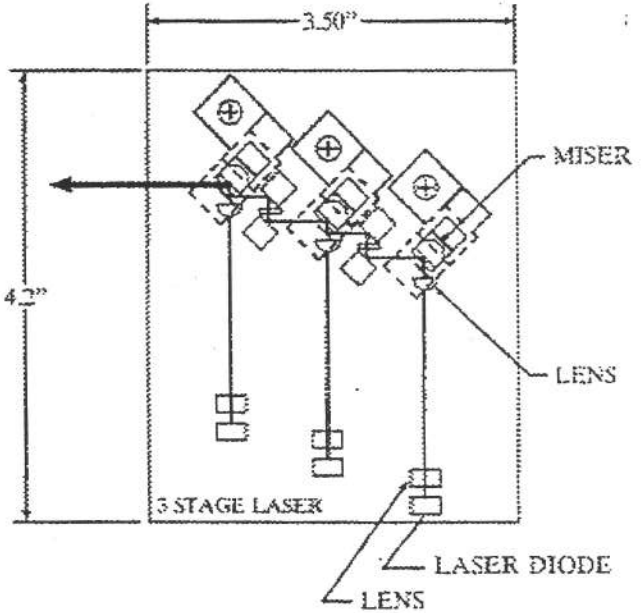
A502.002

One-Watt TEM$_{00}$ Nd:Yag Laser Transmitter Development

Contractor: Lightwave Electronics
Technology: Diode-pumped Nd:yag CW Laser



Single MISER laser stage



Concept: Injection-chaining of three
0.33 Watt MISER laser stages
for 1 Watt frequency-locked operation

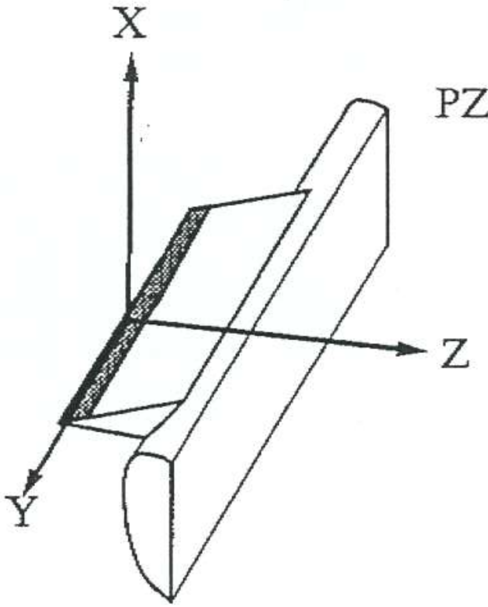
Specifications:
- 0.75-1 Watt TEM$_{00}$ Output Power
- 1.064μm Wavelength
- 25 KHz laser linewidth
- Unattended Operation

J403.01 BD33

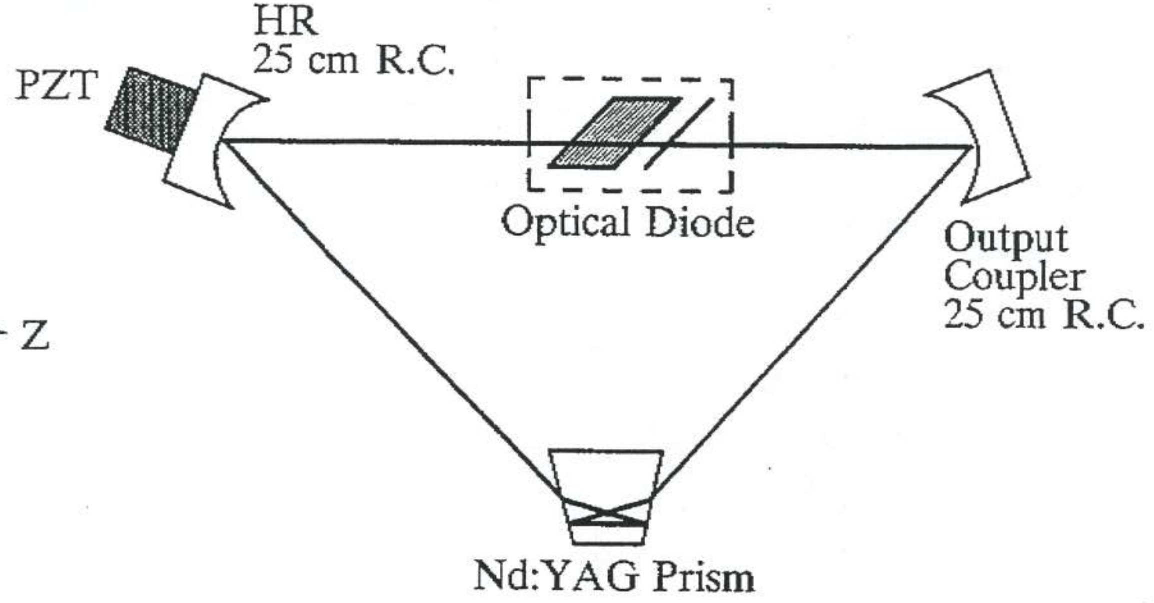
Multi-Watt Single Frequency Diode Pumped YAG Laser

(Schwartz Electro-Optics, Inc.)

Unique Prism Cavity Design Achieves Optimal, Scalable Pumping By Combination of Longitudinal and Transverse Pumping

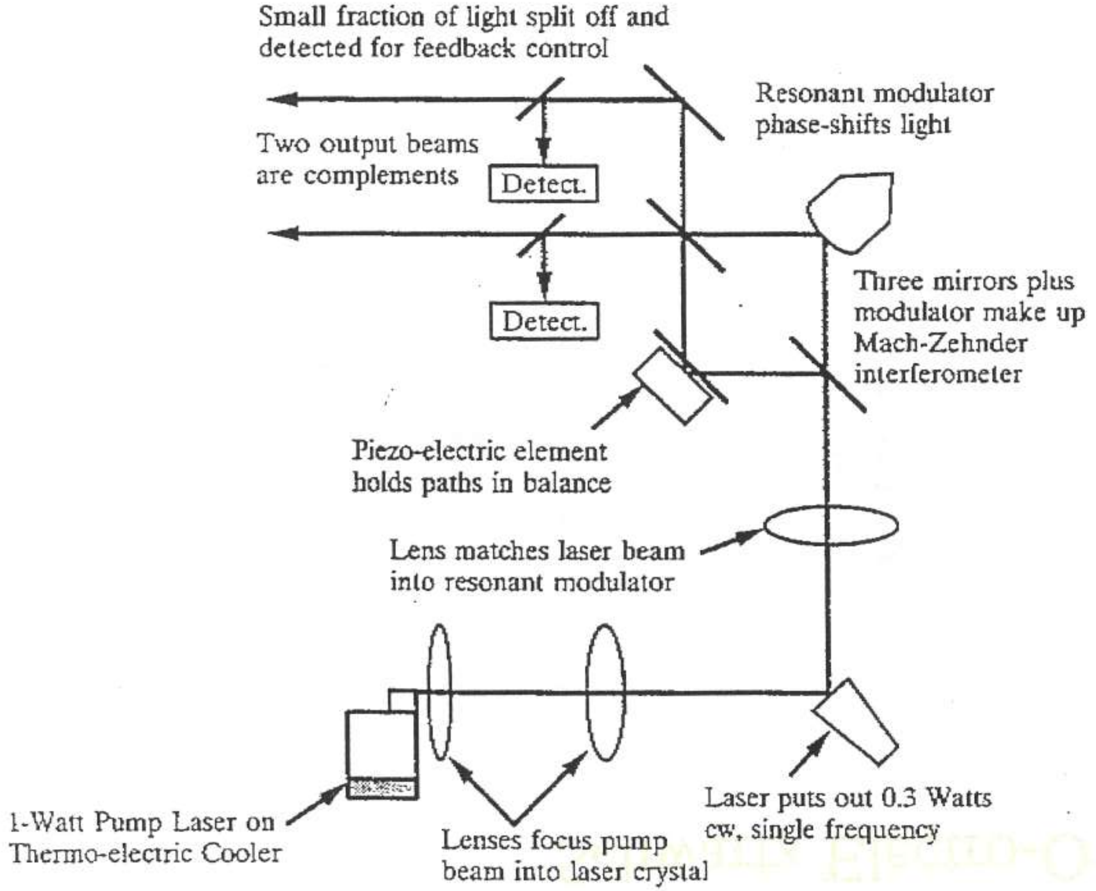


Brewster-cut, Nd gain element
side-pumped by a diode laser bar



Schematic of Prism Cavity Nd:YAG
ring laser (Patent Pending)

Laser Resonant Amplitude Modulator



Small fraction of light split off and detected for feedback control

Two output beams are complements

Resonant modulator phase-shifts light

Three mirrors plus modulator make up Mach-Zehnder interferometer

Piezo-electric element holds paths in balance

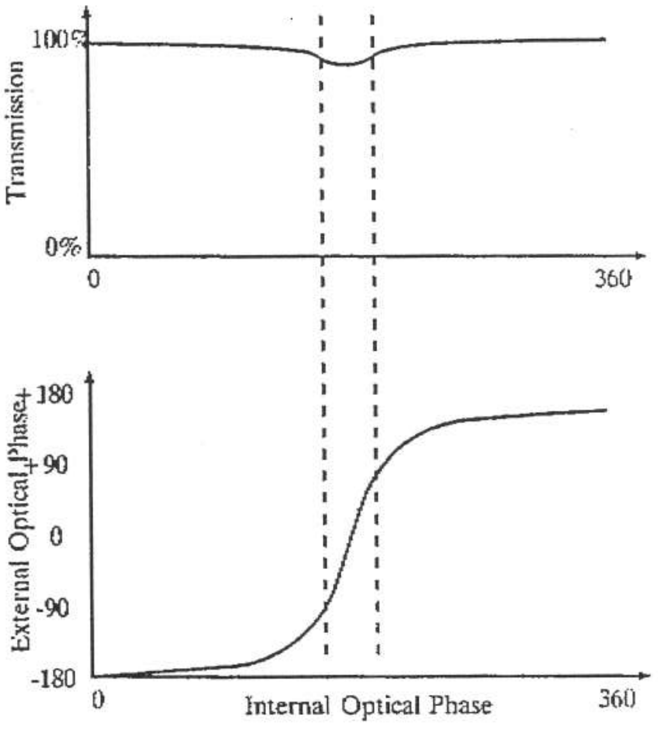
Lens matches laser beam into resonant modulator

1-Watt Pump Laser on Thermo-electric Cooler

Lenses focus pump beam into laser crystal

Laser puts out 0.3 Watts cw, single frequency

Layout of integrated laser/modulator in amplitude modulation configuration

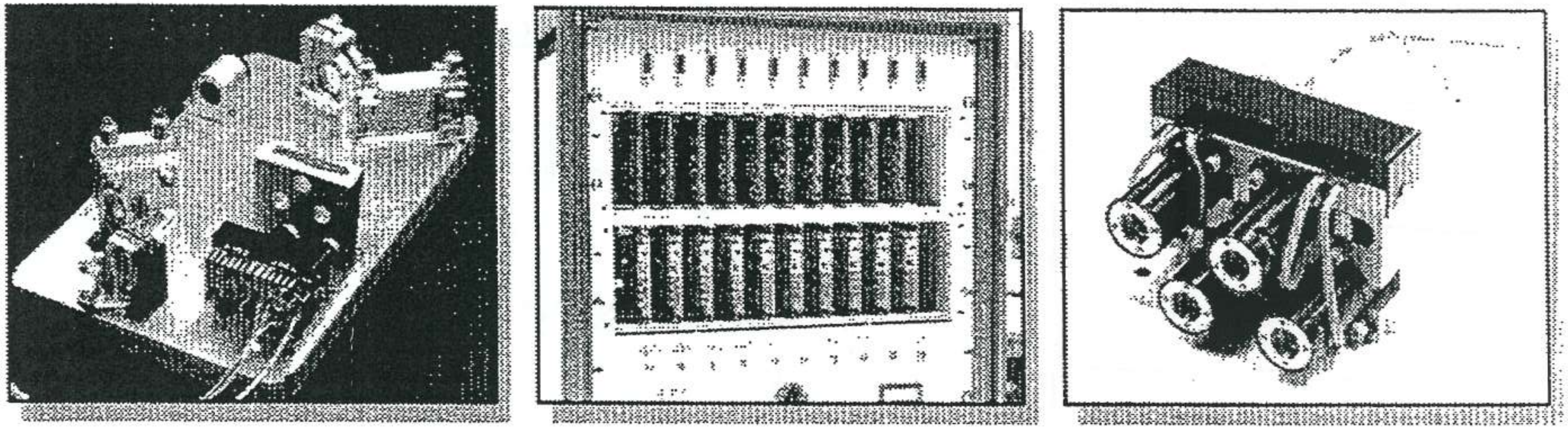


Amplitude and Phase of the light reflected from the etalon as a function of the internal phase change. Phase changes quickly near the resonance.

F403.020

Incoherent Power Combining

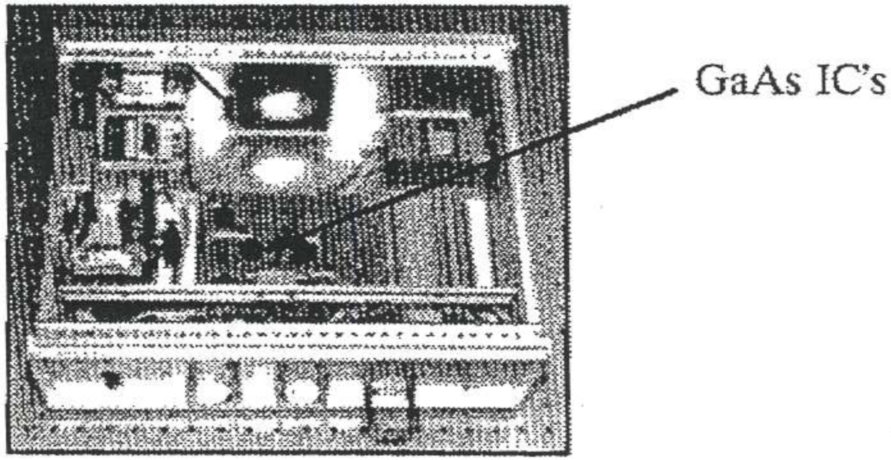
Power Combiners (WDM) are a basic Tx/Rx building block for direct detection laser communications requiring 3-5 watts of source diode power



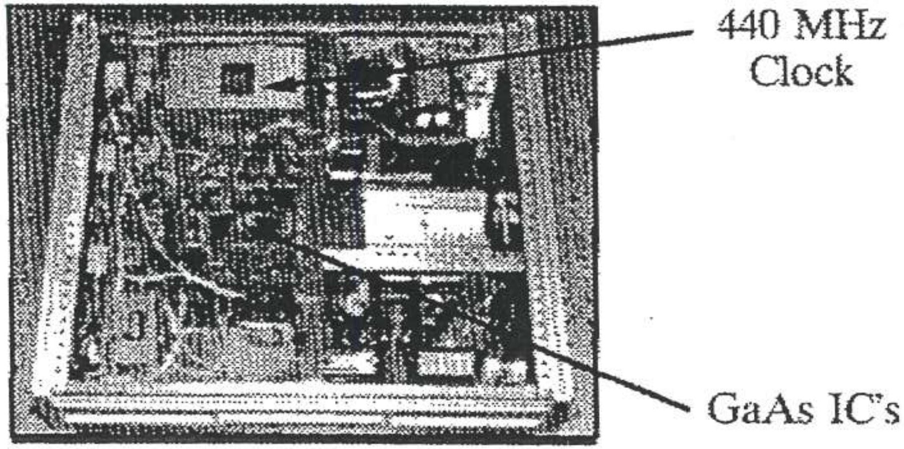
Grating Laser Beam Combiner (GLBC)

- 0.25 Watt ouput, 50% duty cycle; scalable to 0.5 - 1.0 Watt
- Electronics can run at a submultiple of full data rate
- Graceful degradation, each laser coherently fills aperture
- Lightweight/compact design possible
- Performance is insensitive to laser diode instabilities, i.e. wavelength

Wideband Optical Receiver Development
(Johns Hopkins University)

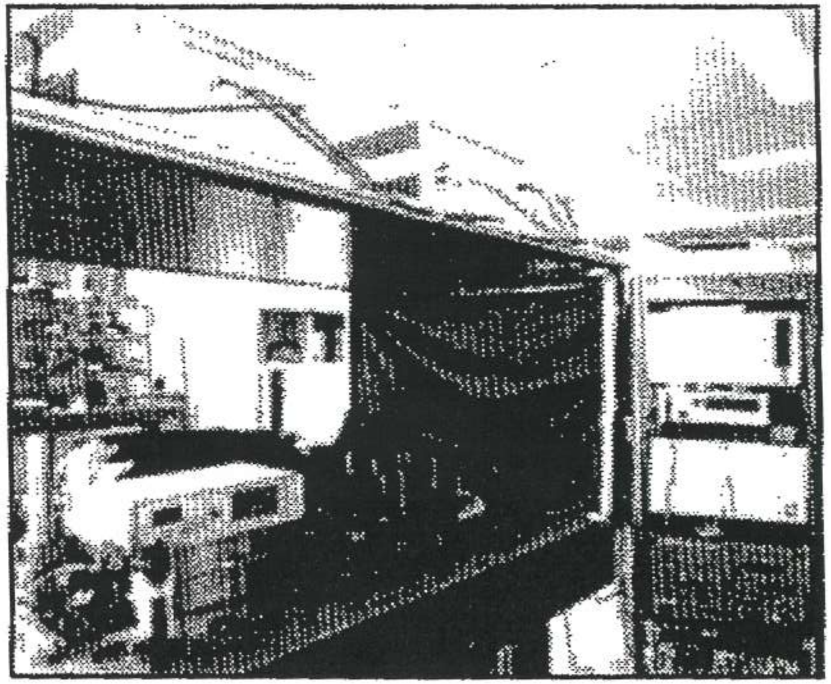


220 Mbps Qppm Transmitter



220 Mbps Qppm Receiver

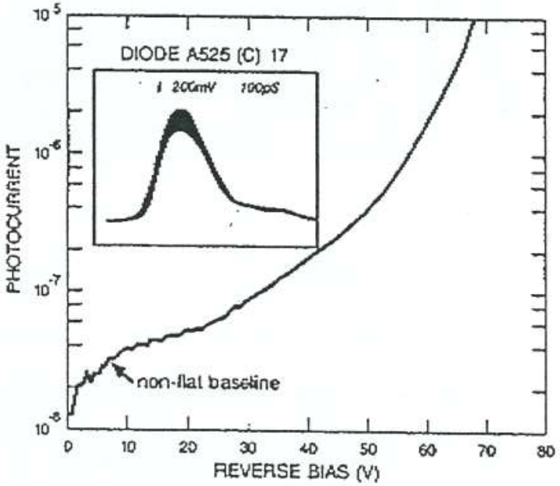
A502.04 BD68



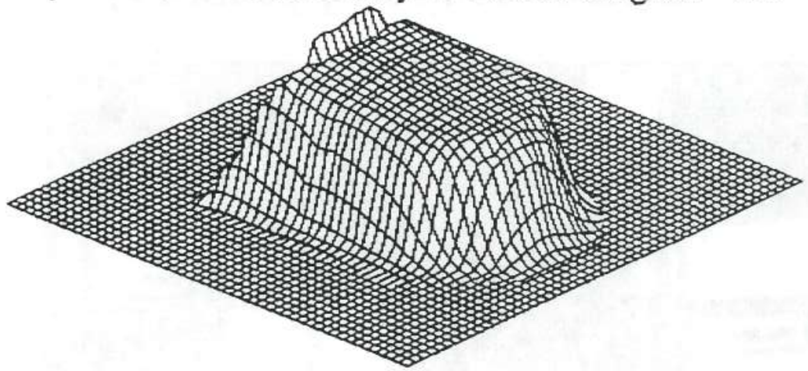
Goddard Receiver Performance
Measurement System

AlGaAs Staircase APD
Characteristics of 10-stage Device

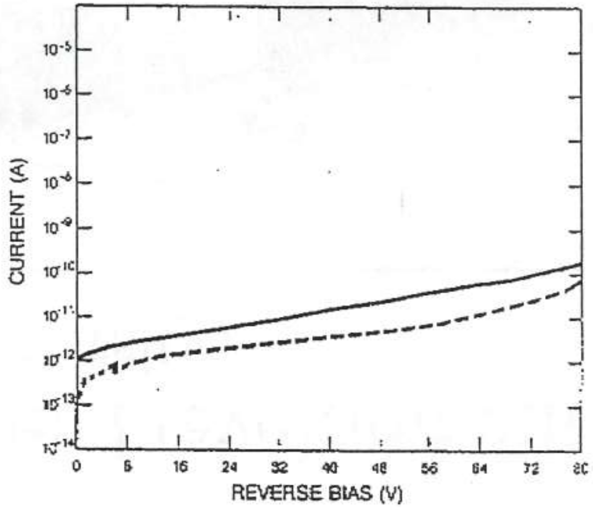
Photocurrent vs. Reverse Bias at 632.8 nm
Inset: response to input 100 ps pulse at 550 nm, -45 V bias



Spatial Gain Uniformity in Active Region ~ 1%



Dark Current @ 25 C



Recent Results:

Evidence of k = 0.01 obtained
Doping-interface-dipoles of C^{+4} may reduce k
Smaller-than-anticipated conduction band discontinuity at interfaces

Higher required electric fields with attendant hole impact ionization

B403.003

GSFC

AT&T AlGaAs Staircase APD

GOALS:

Quantum Efficiency	80%
Gain	300
Excess Noise	3dB better than Si APD
Bandwidth	>500 MHz
Active Area	10^{-4} cm^2
Wavelength	830nm

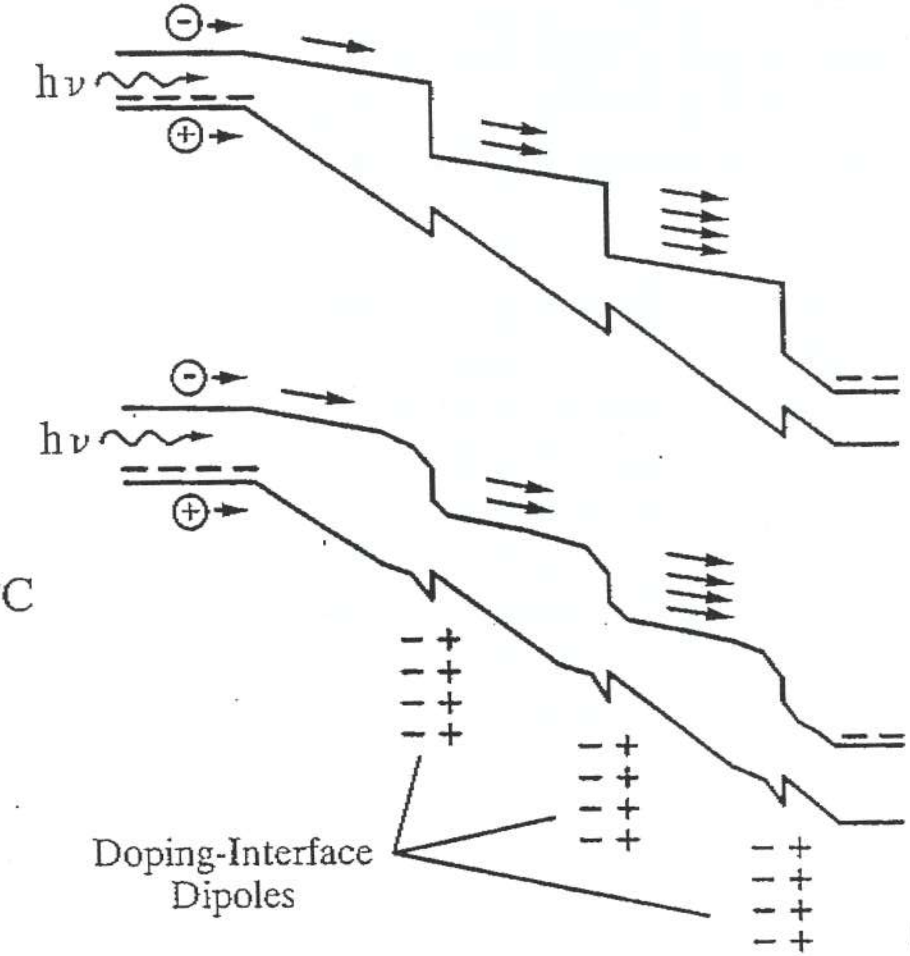
FABRICATION METHOD:

MBE on n$^+$- Si doped substrates
Substrate growth temperature of 600°C

Device processing into mesas using standard photolithographic technique and wet etching

DID's formed by depositing Si donor and Be acceptor atoms

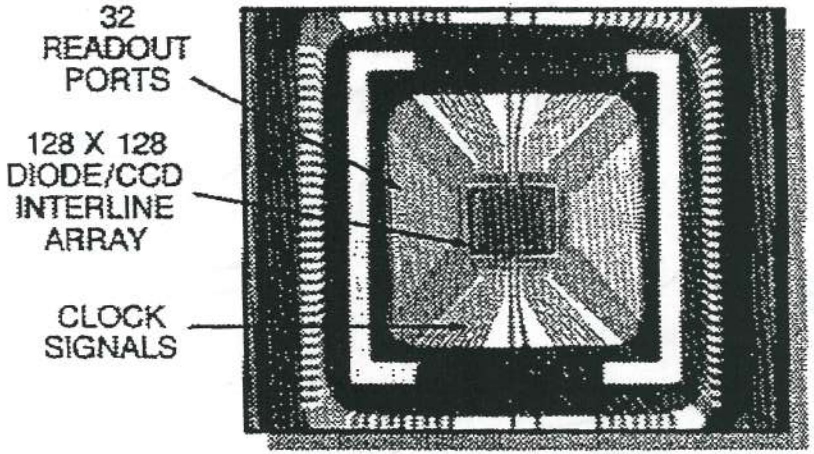
Band Diagram



B403.001

Multi-Functional Area Array Detector for Sub-Arc Second Pointing

POCAAD - Proof Of Concept Area Array Detector

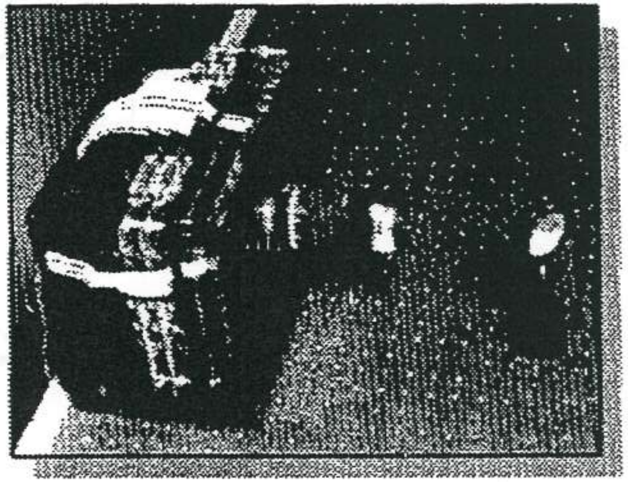


Requirements

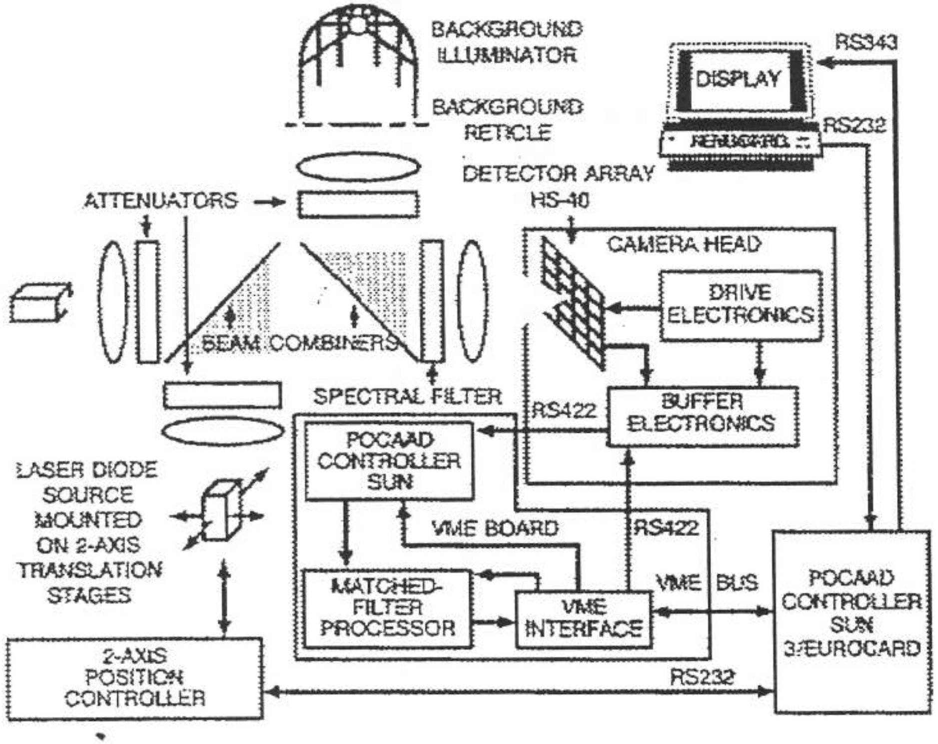
- 1000μRAD Acq FOV
- 0.5μRAD Track Noise
- 10^{-12}Watts Optical Power
- 150μRAD Point Ahead Range
- 0.25μRAD Point Ahead Accuracy

"POCAAD" Design

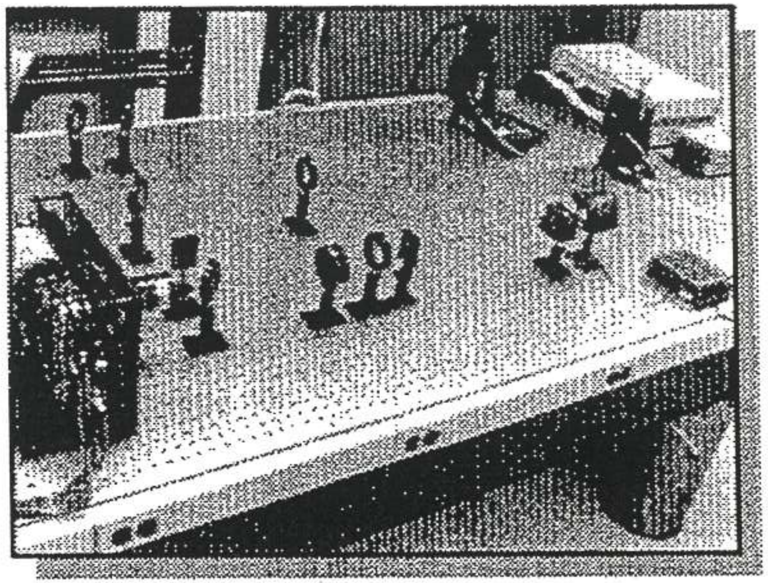
- 128 x 128 Diode/CCD Array
- Interline Architecture, 64 Port Parallel Readout
- Rapid Charge Transfer (μs)
- 72% Fill Factor
- 22 e RMS Readout Noise, 1-5 KHz Frame Rate
- Fixed Pattern Noise Compensation, Offset and Gain
- Matched Filter Processor for Centoid Estimation



POCAAD System Demonstrator
(Kodak)



POCAAD System Layout

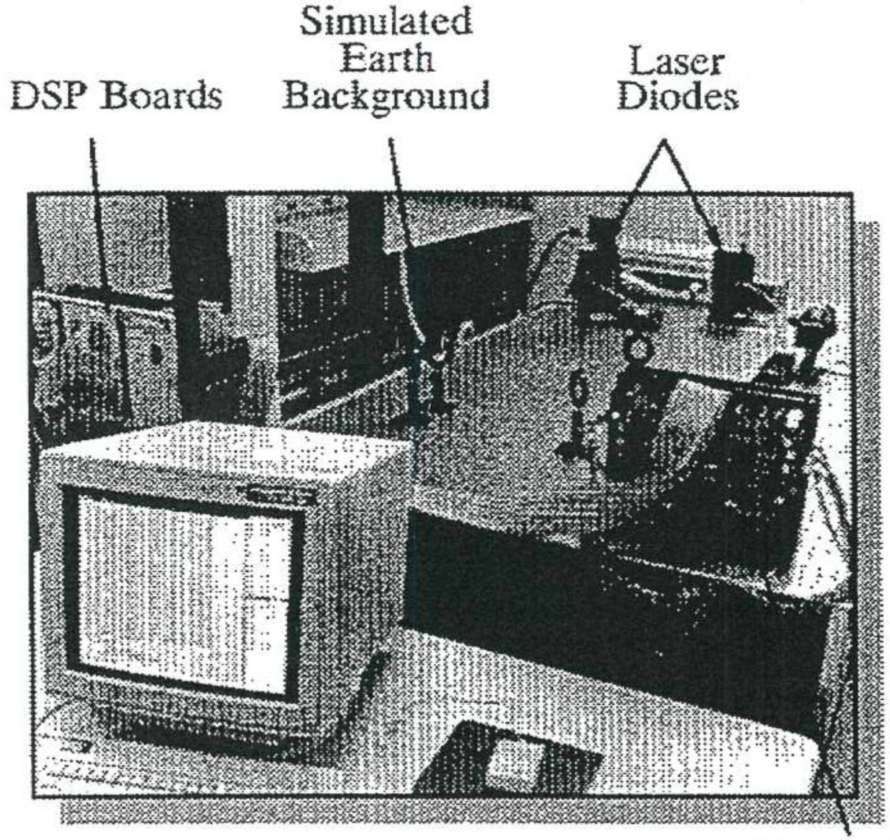


System Demonstrator

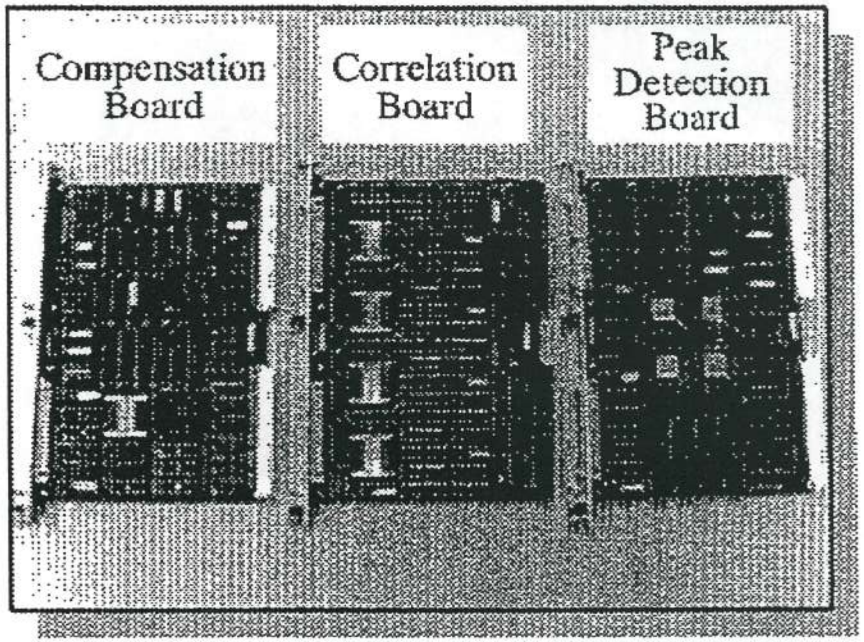
A502.25 BD68

POCAAD System Demonstrator

(Kodak)



SUN 3/110 Controller



DSP Boards

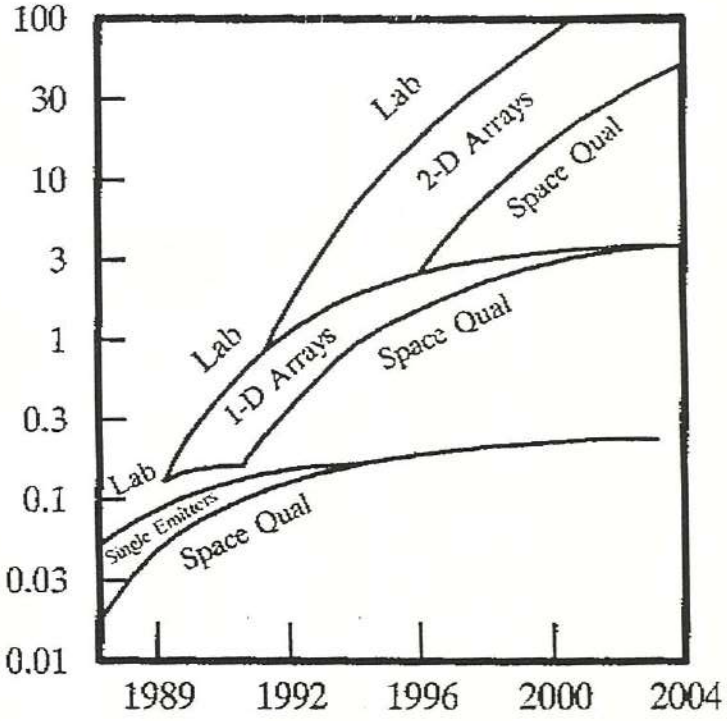
Semiconductor Laser Power Projections

Technology Status:

Single Emitters (Developed)
- 100 mW Reliable Power

1-D Arrays (In Development)
- 1-3 W Reliable Coherent Power

2-D Arrays (To Be Developed)
- 10-100 W Reliable Coherent Power



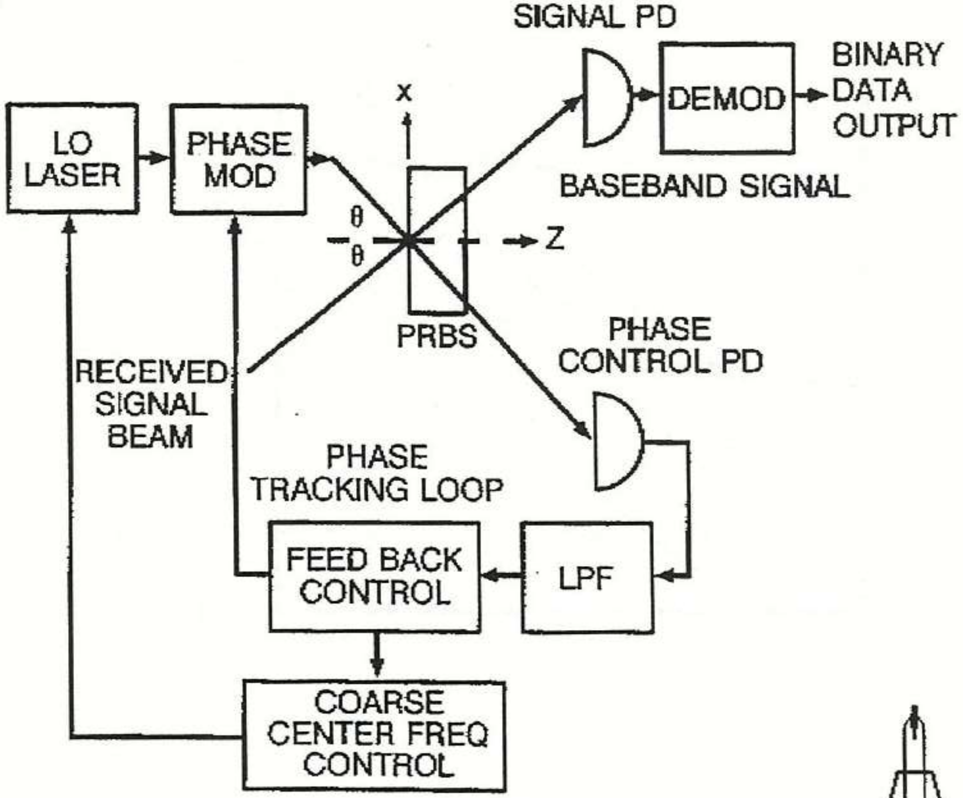
Coherent Optical Communication Receivers With Photorefractive Beam Combiners

(Johns Hopkins University)

石原
responsibility 速いはず.

Features:

- Precise Mode Matching for Maximum Heterodyne Efficiency
- Automatic Control of Arrival Angles of the Signal and LO Fields
- SNR Adjustment by Simple Rotation of PR Crystal
- Submegahertz Linewidth, One Watt Lasers Enable the Slower PR Materials with Higher Nonlinearities; e.g., Barium Titanate
- PR Implementation Uses All the Signal Power



A502.007

3-2

Optical space communications research activities at INTELSAT

Shigeyuki Akiba
John L. Stevenson
Robert A. Peters

INTELSAT

IWOSC '90

December 6 and 7, 1990, ATR, Kyoto

Optical Space Communications Research Activities at INTELSAT

Shigeyuki Akiba, John L. Stevenson, and Robert A. Peters

INTELSAT
R & D Department
3400 International Dr., N.W.
Washington D.C., 20008
U. S. A.

Abstract

INTELSAT R&D has sponsored studies and hardware development on microwave ISLs since 1974 and optical ISLs since 1982. This paper reviews the goals and accomplishments mainly of optical ISL programs and examines some difficulties and possible time tables for the incorporation of ISLs in the INTELSAT system. The R&D activities has covered a wide range of technology scope on optical inter-satellite links, including technology survey, spacecraft interactions, antenna tracking and optoelectronic components. Among them semiconductor lasers as a high power light source have been extensively studied and their lifetests are still under way. First we address possible application scenarios of optical space communications and they are followed by individual programs performed under contracts, joint works and in-house efforts. The research activities have shown that the incorporation of an optical ISL on a communication satellite is quite feasible, though the time of implementation is not clear.

Shigeyuki AKIBA gained the B.S., M.S. and Ph.D. degrees from the Tokyo Institute of Technology, Japan in 1974, 1976 and 1984 respectively. He has been employed at the KDD Meguro Research and Development Laboratories since 1976, specialising in the development of semiconductor optoelectronic devices for optical fibre communications systems. Dr. Akiba was a Fellow at CAES, Massachusetts Institute of Technology, from 1980 to 1981. He currently holds an Assignee position as a Microelectronics and Reliability Specialist with INTELSAT in Washington D.C.

John STEVENSON is Manager: Microelectronics, Antennas and Propagation R&D at INTELSAT. He holds a B.Sc. degree from the University of Leicester (U.K.) and was awarded a Ph.D. in Electrical Engineering from the Imperial College of Science and Technology, University of London in 1973. His responsibilities at INTELSAT include the monitoring of in-orbit satellite reliabilities. He has also been active in developing improved reliability assurance and certification procedures for a number of advanced vacuum electronic, optoelectronic, electrochemical and semiconductor devices.

Optical Space Communications Research Activities at INTELSAT

by

Shigeyuki Akiba
John L. Stevenson
Robert A. Peters

IWOSC '90
ATR, Kyoto, Japan
December 1990

Goals of INTELSAT R&D

Decrease user costs through

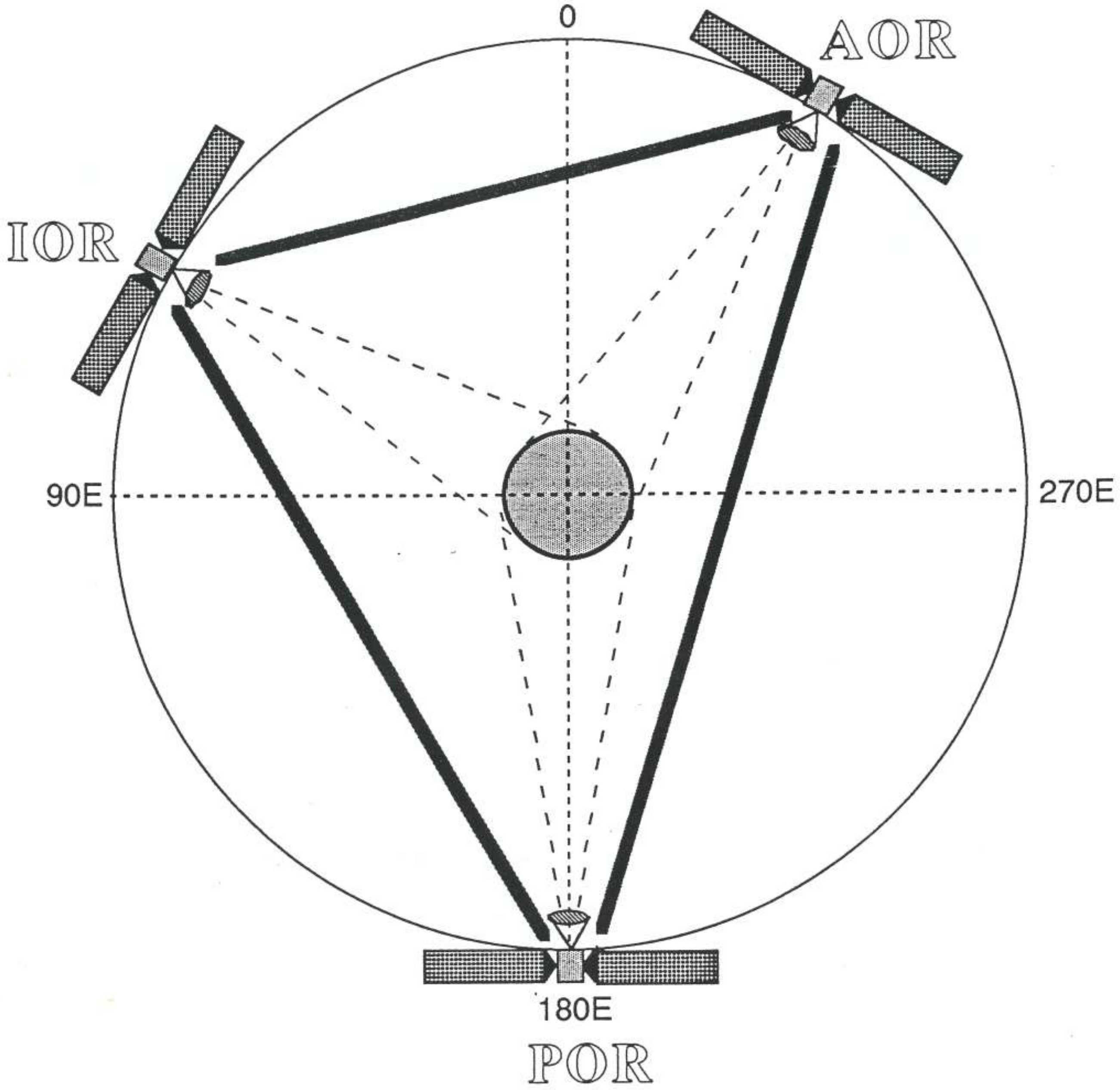
- *improved reliability*
- *new services*

By

- *identifying promising new technologies*
- *determining viability of new technologies*
- *demonstrating the reliability of new technologies*
- *establishing specifications to implement technologies*

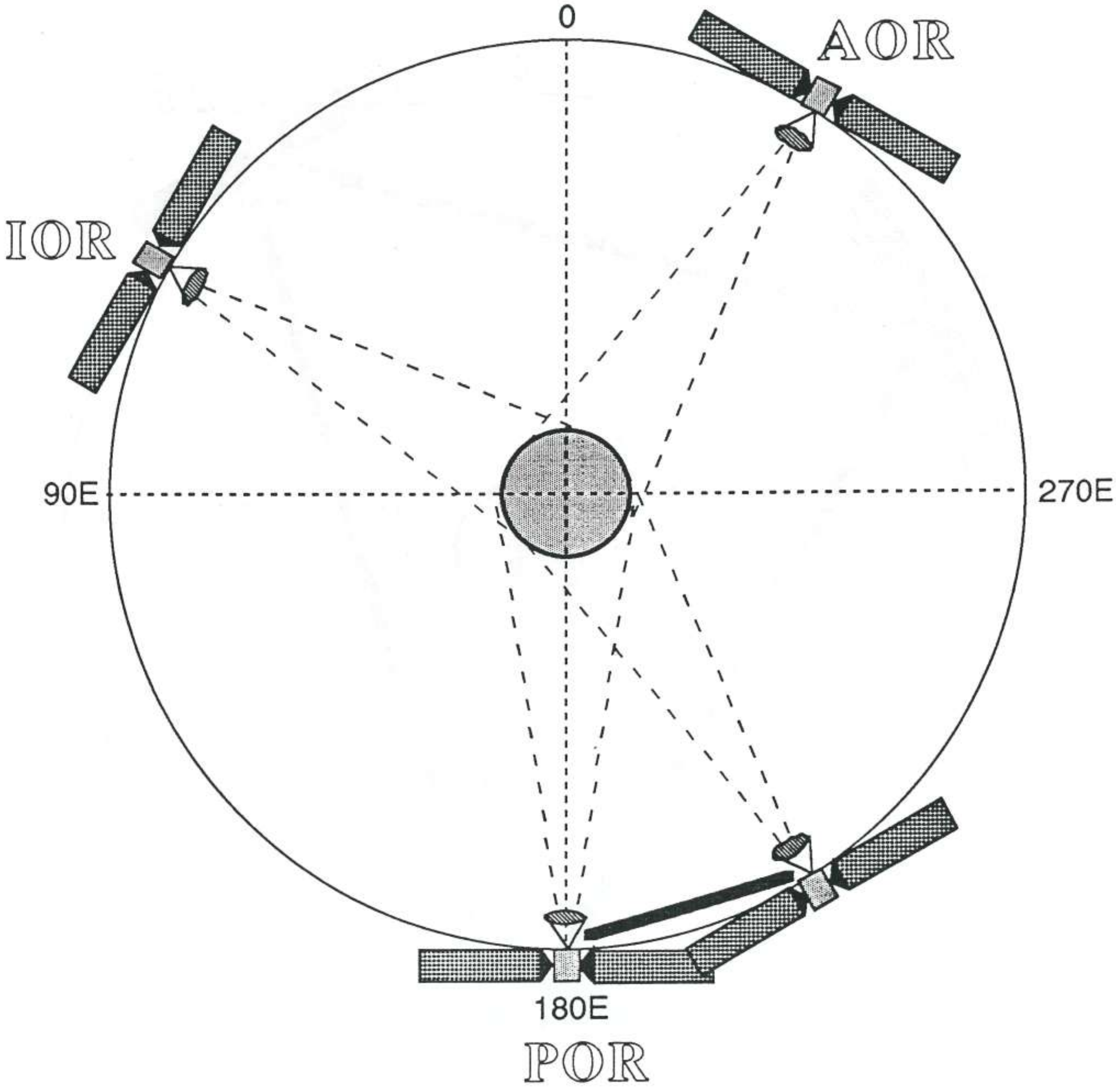
Leading to incorporation of new technology in a satellite procurement.

Inter-Oceanic ISL

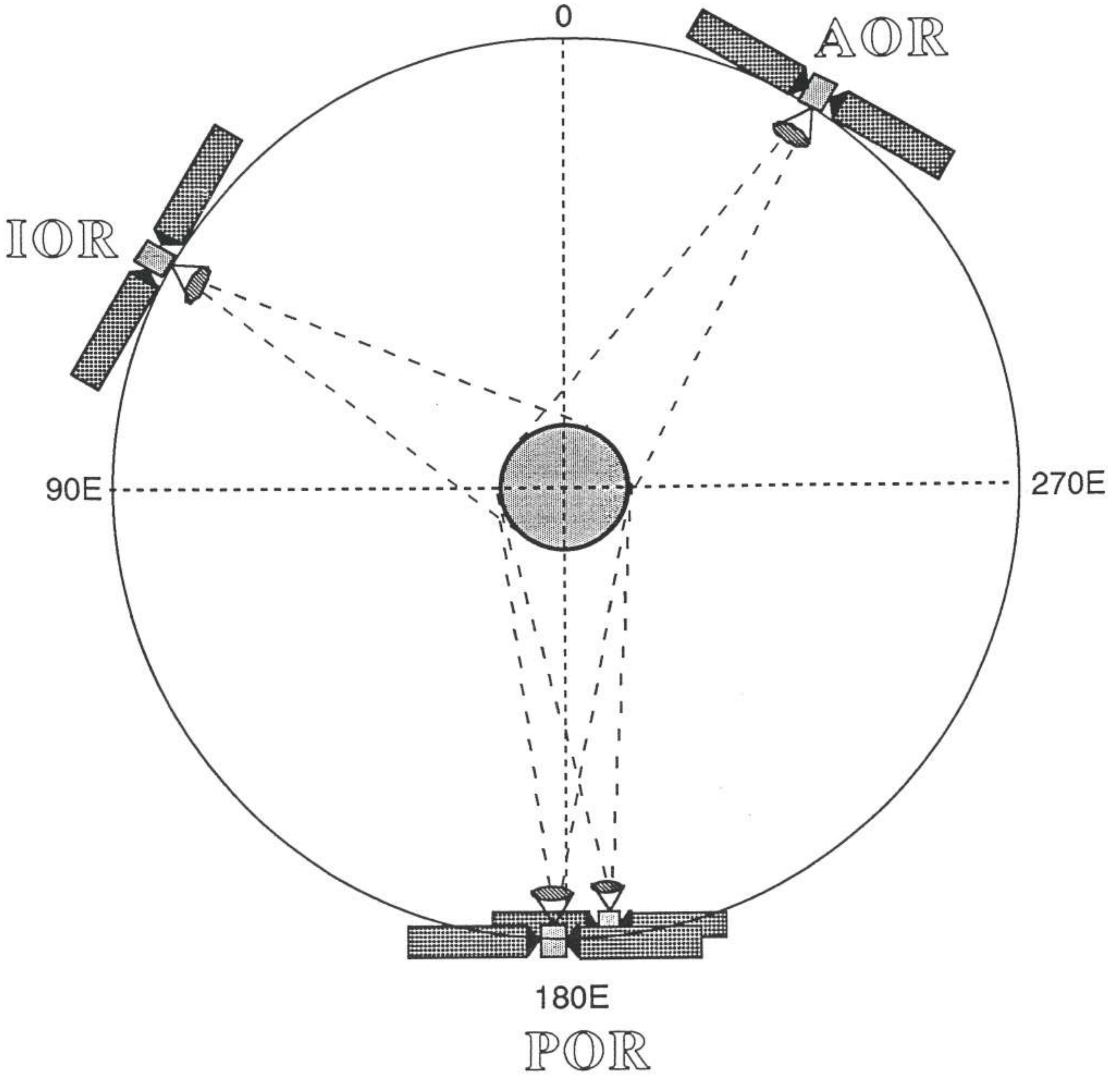


13 satellites

Regional ISL

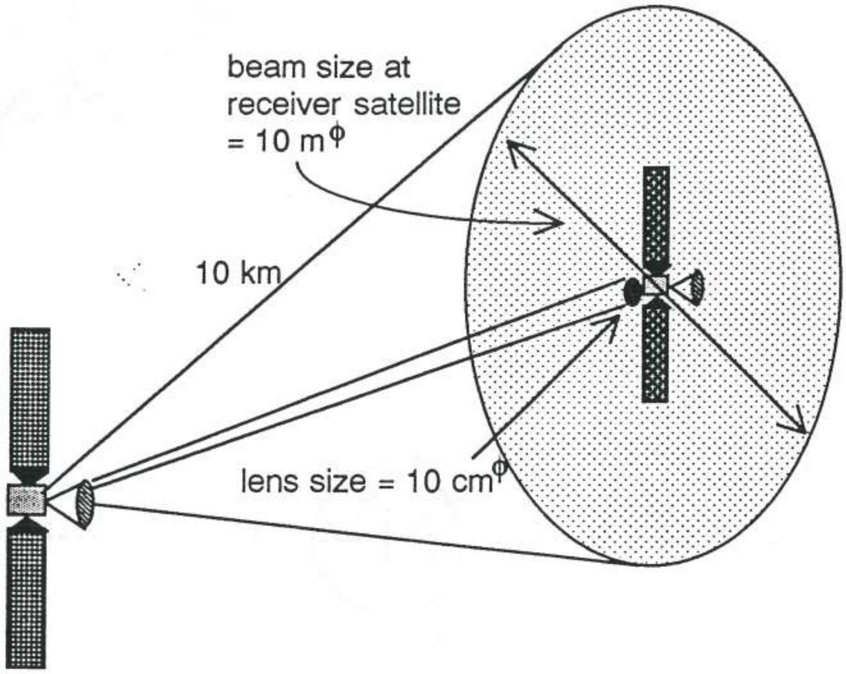


Collocation ISL



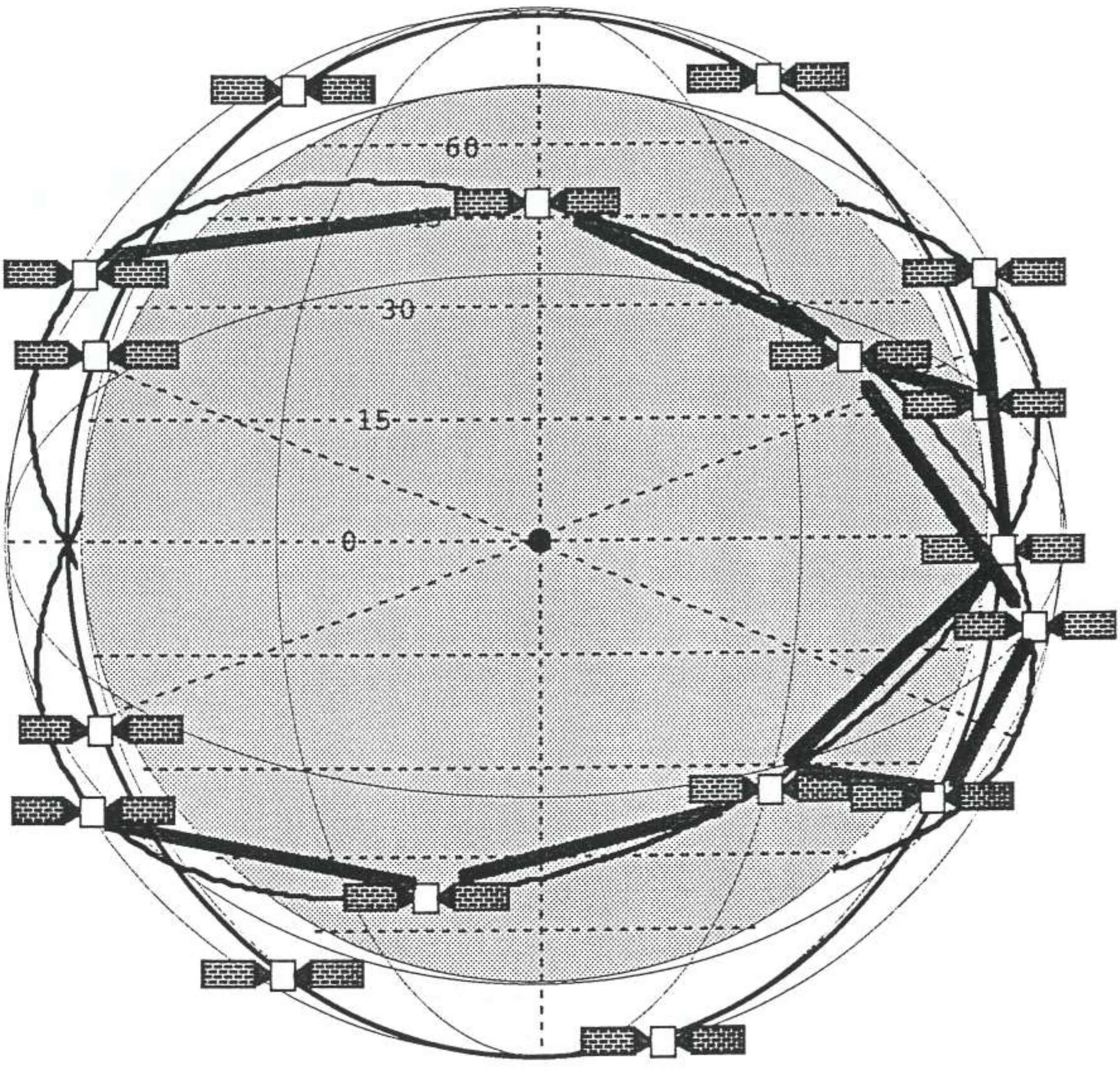
Ray Optics of Collocation ISL

0.01 rad



18dB C/N ~

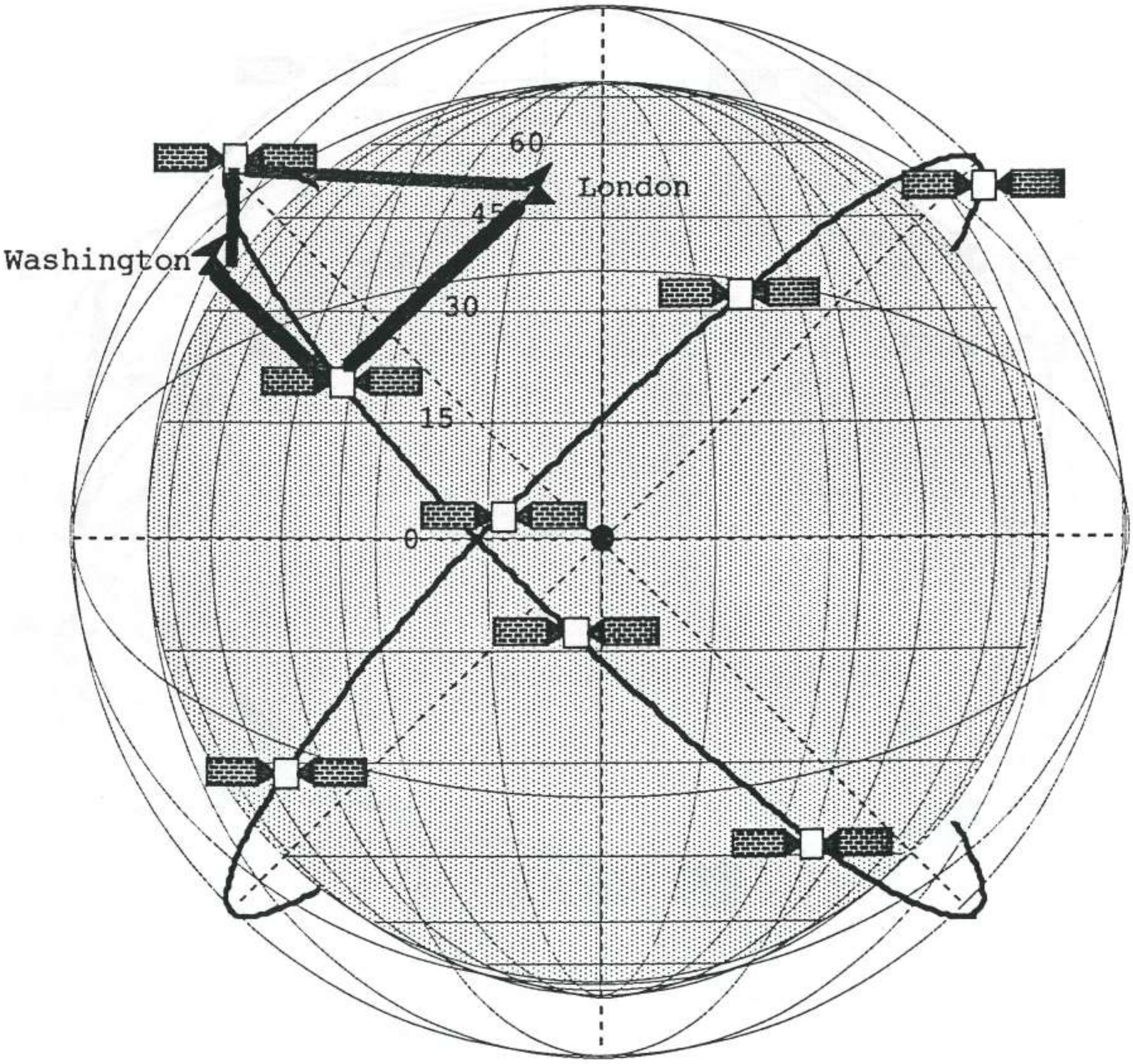
Low Earth Orbit (LEO) ISL



Large delay.

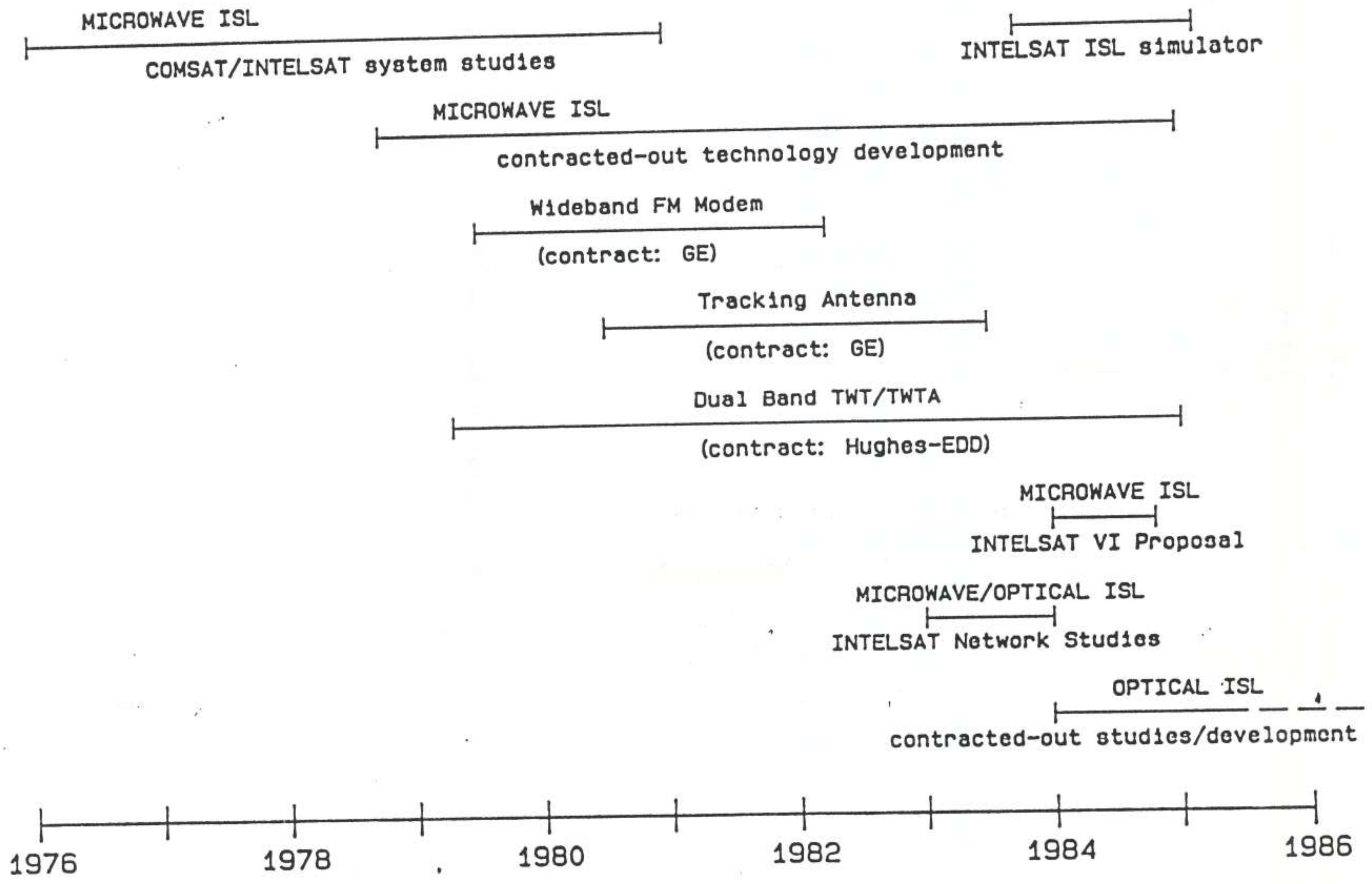
. Weight . power requirement . → optics
有[illegible]用!

Space-Ground ISL

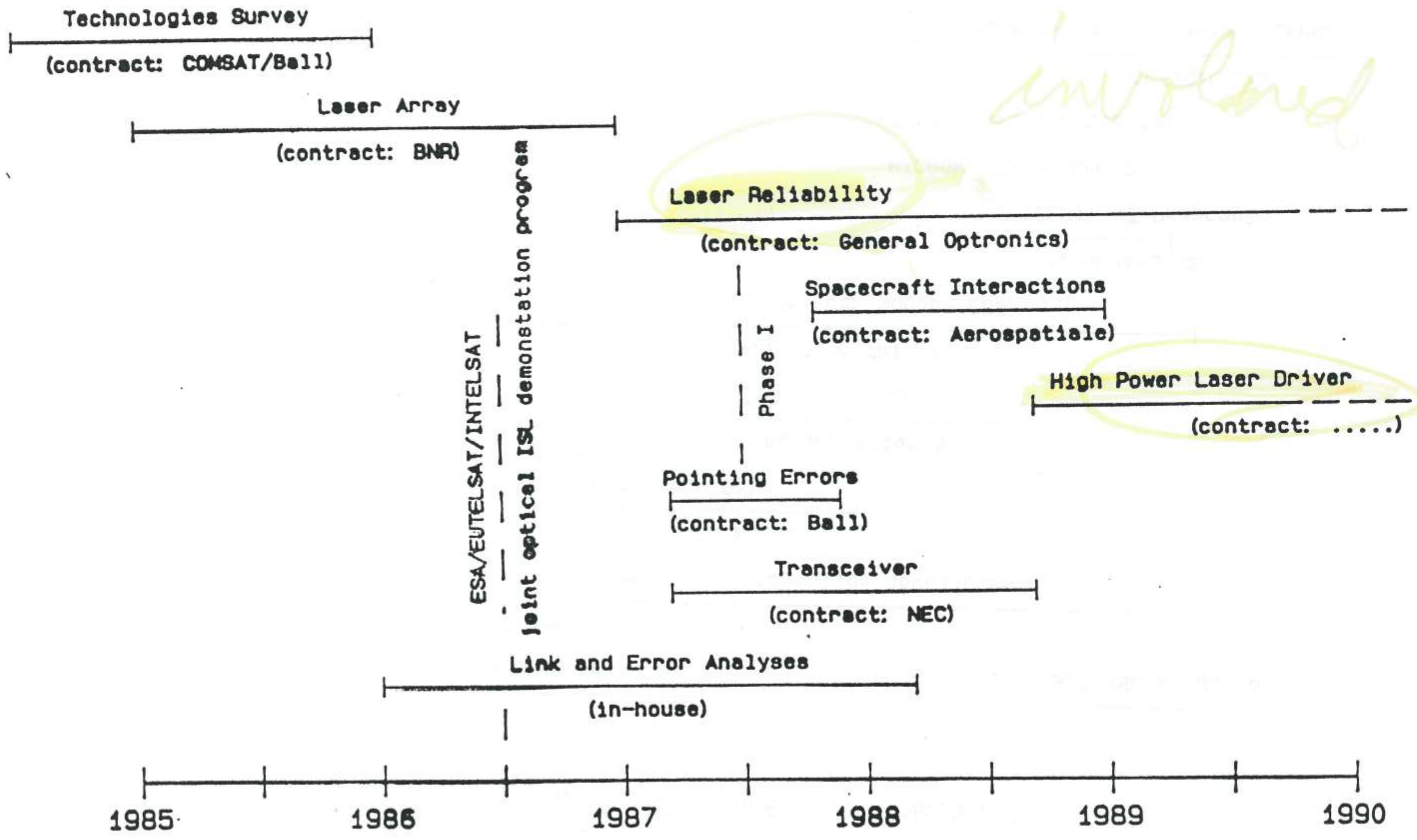


not good for Intelsat study.

INTELSAT ISL TECHNOLOGY DEVELOPMENT, SYSTEMS STUDIES AND SPACECRAFT ANALYSIS



INTELSAT OPTICAL ISL TECHNOLOGY DEVELOPMENT AND PERFORMANCE ANALYSES



involved

INTELSAT optical ISL R&D effort limited in scope, to cover critical issues:

- *ISL terminal/host spacecraft interactions*
- *Tracking disturbances; error performance*
- *Opto-electronic component performance and reliability*

. . . some technologies required for optical ISL are already well developed, and others will be "spin-offs" adapted from related efforts. . .

INTELSAT VI Microwave ISL Modification Proposal, Hughes Aircraft

- 72 MHz two-way link
- up to 24 degree separation
  (with sun outage)
- heterodyne implementation
- 10 W TWTAs, 23/32 GHz
- 2.0 meter diameter antennas
- one east facing spacecraft;
  one west facing spacecraft
- 98 kg and 140 W DC per spacecraft

This was given up.

INTELSAT R&D in Optical ISLs

Area	Years	$	Company
Link, Coding, burst error and regulatory analysis	86-88		In-House
Technology and Hardware Study	84-86	100k	COMSAT/ Ball (USA)
Coherent Laser Array (200mW)	85-87	150k	BNR (Canada)
Joint ISL Program	87-?		ESA /EUTELSAT
Laser Reliability (60-100mW)	87-?	340k	Laser Diode (USA)
ISL-Spacecraft Interactions	87-88	100k	Aerospatiale (France)
Antenna Pointing Accuracy/burst noise	87-88	100k	Ball (USA)
Optical ISL Transceiver	87-88	75K	NEC (Japan)
Power supply for 1 W stabilized laser transmitter	88-?	155K	ANT (Germany)

Technology and Hardware Study

(COMSAT/Ball)

Examined:

- *possible laser and detector sources*
- *acquisition and pointing*
- *link budget/hardware sizing*
- *wavelength division multiplexing hardware*
- *contamination of optics*
- *system designs (mass/power/volume)*

Results:

Established viability of optical ISL, but showed mass to be significantly greater than initially estimated.

Laser Diode Array
(Bell-Northern Research)

- **high power laser diode array (200 mW)**
- **monolithic (single chip)**
- **coherent output (coupled stripes; diffraction limited output)**
- **approach:**
  - *individually contacted stripes*
  - *external optical "mixing regions"*
- **Results:**
  - *300 mW output power achieved*
  - *1 degree far field beam width achieved*
  - *slow dynamics of beam pattern control with bias*
  - *thermal characteristics of lasers impacted by external mixing region*

Spacecraft Interactions
(Aerospatiale)

- **Study dynamic interaction between bus (platform) and ISL terminal (package)**
- **Approach:**
  - *Extensive modelling exercise (low level disturbances at up to 250 Hz important)*
  - *Experimental and theoretical effort using TDF spacecraft structural model (for various potential locations of ISl terminal)*
  - *Optimize ISL pointing control scheme (coarse and fine; "active" rejection of mechanical disturbances; also passive isolation)*

Antenna Tracking/Burst Noise
(Ball Aerospace)

- **link simulation**
- **tracking sub-system test**
- **determine pointing probability distribution**
- **approach:**
  - ***optical table demonstrator set up***
  - ***fine steering mirror, avalanche quadrant cell detector***
  - ***BER and simultaneous pointing measurements, with/without simulated solar conjunction***
- **results:**
  - ***one-sigma pointing errors very small in presence of "typical" disturbances***
  - ***AC tracking permits tracking during solar conjunction***
  - ***good agreement between measured and predicted performance of tracking sub-system***

SPIE

ESA/EUTELSAT/INTELSAT Joint ISL Program

- **Discussions started in 1985, completed agreement on Phase I in 1987**

Phase I: *Mission and system studies (1987-88) to quantify system advantages of optical ISLs and define experimental payload based on mission.*

Phase II: *Critical payload hardware development (1988-89) and detailed definition of associated satellites.*

Phase III: *Flight model optical terminal development and subsequent integration.*

Phase IV: *In orbit demonstration.*

ESA/EUTELSAT/INTELSAT Joint ISL Program

- **INTELSAT and EUTELSAT to provide the ground segments and ESA to provide the space segment.**

- **A contract let to a consortium led by Telespazio, and including MATRA, Selenia, and CISE in 1987 and completed in 1988.**

Phase I Results:
- *Optical ISL mass and power requirements consistent with other studies.*
- *Some progress toward quantifying advantages of an ISL.*
- *Value of improved earth station elevation angles highlighted.*

Present Status: *In limbo - no second GEO terminal available, but ESA SILEX program progressing.*

Transceiver
(NEC)

- **QPPM transceiver**
- **30 mW semiconductor laser diode**
- **proof-of-concept demonstration**
- **approach:**
    - *conventional technologies*
    - *400 Mbit/s capability* -40dBm.
    - *100 Mbit/s hardware*
- **results:**
    - *design completed*
    - *hardware built and tested*

Semiconductor Laser Reliability
(General Optronics)

- **full reliability demonstration** — (Laser Diode Link, co)

- **using a new INTELSAT-developed life test method**

- **40 mW single diodes; 60 mW diode arrays**

- **approach:**

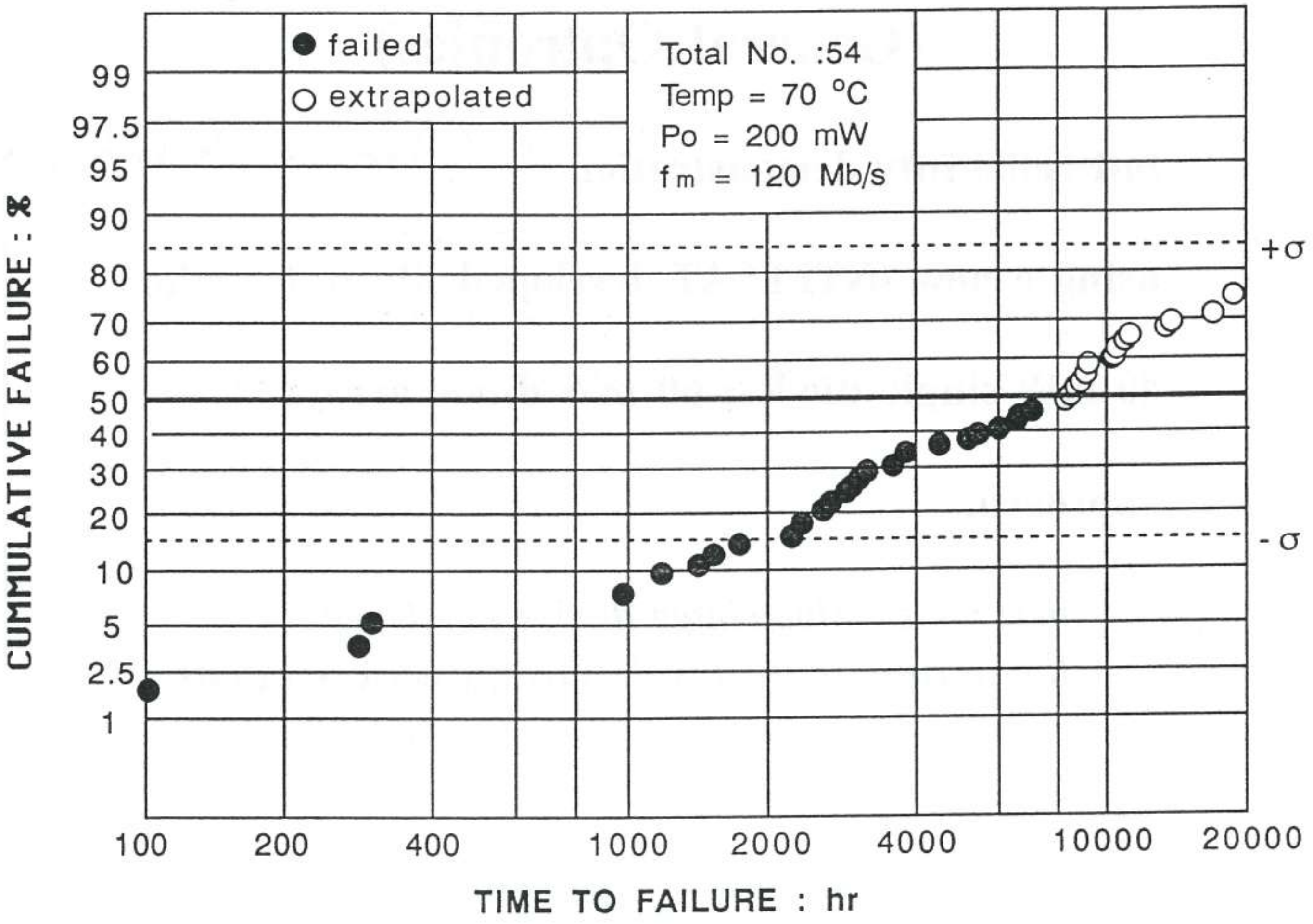
  - *new wide-stripe single diodes developed*
  - *life testing under 120 Mbit/s pulsed conditions*

- **results:**

  - *100 mW output easily attained*
  - *excellent linearity; good modulation characteristics*
  - *close to single mode operation (but not diffraction limited)*
  - *lasers easily survive initial screening test*

Cummulative Failure Plot of Wide Stripe Lasers

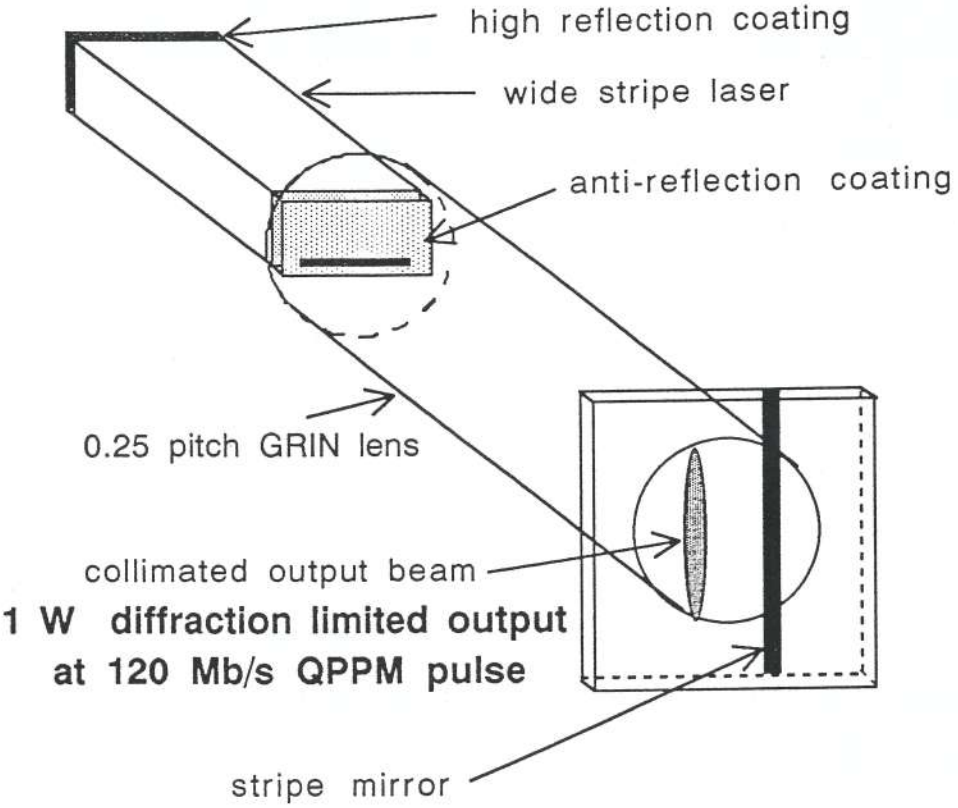
(Laser Diode Inc.)



INTELSAT

Long Term Reliability Study of Laser Diode Transmitter and Laser Diode Driver Electronics Package

(ANT Telecommunications)



In-House Efforts

- Examined basic feasibility of all technologies required for an optical ISL and prepared limited R&D program (1981-83).
- Modeled: burst errors; impact of coding on BER in a burst error environment; stability of tracking with two interacting terminals, each with its own tracking noise.
- Investigated requirements on optical ISL performance based on ISDN requirements.

Results

- No significant problems discovered (but block coding found to be much less effective than for microwave links)

Optical ISL/Onboard Processing

Regeneration is necessary because ISL must work with existing standards and not add significant degradation.

Baseband switching is necessary because of connectivity. INTELSAT satellites typically have 4 to 6 different beams at C-Band and 2 or 3 at Ku-Band. If complete connectivity between 4 beams (no ISL) is required, there are 16 inter-connections. If there is an ISL and connections are required between 8 beams (4 on each satellite) there are 64 inter-connections.

Summary

- **INTELSAT R&D indicates that there are no serious problems to incorporating an optical ISL on an operational spacecraft.**
- **An optical ISL is expected to be preceded by on-board regeneration and switching. The required technology (for small earth stations) is probably less mature than technology for an optical ISL.**

5 years ~10 leading time is long

- **INTELSAT's method of procuring spacecraft makes it harder to implement an ISL.**
- **INTELSAT is not likely to implement an ISL on an operational spacecraft before 2005.**
- **To implement an ISL by 2005, a major effort should begin soon.**

3-3

Recent developments in laser technologies for optical space communications

David L. Begley

Ball Aerospace
Systems Group

IWOSC '90
December 6 and 7, 1990, ATR, Kyoto

RECENT DEVELOPMENTS IN LASER TECHNOLOGIES FOR OPTICAL SPACE COMMUNICATIONS

D.L. BEGLEY
BALL AEROSPACE SYSTEMS GROUP

ABSTRACT

Lasers have been considered for space communications since their realization in 1960. However, it was soon recognized that, though the laser had the potential for data transfer at extremely high rates, much work was required for space-qualified hardware. The critical selection of a laser technology depends heavily on the specific application and general mission requirements. General characteristics associated with individual laser technologies can be used to evaluate application to free-space communications, including capability of a number of operating modes, qualifiable for a variety of applications, high efficiency, and long life. Although each laser technology has unique characteristics which may make it superior in a single aspect, solid state and semiconductor lasers are the most appropriate.

Laser diode technology has made dramatic advances in the past ten years. With increased performance and uniformity of epitaxial growth brought about by metal-organic chemical vapor deposition and molecular beam epitaxy, very precise control of the emission characteristics from laser diodes can be achieved. Semiconductor

lasers offers: the ability to accommodate very high data rates, low weight, small size, high efficiency and increased reliability compared to other base technologies. There are however, limitations that must be overcome when considering the utilization of semiconductor lasers. Analysis of common communication-laser requirements indicates that output beam quality and power, and spectral distribution are critical issues.

In the past, solid state lasers were pumped by high-energy flashlamps. Energy not absorbed by the active medium is converted to heat which must be dissipated. For extended, reliable operation of laser systems with an increase in flexibility, a solid state replacement for gas lamps would provide many advantages. Laser diodes are attractive as solid-state laser pumps because of the narrow spectral emission width and increased reliability inherent to semiconductor technologies. As the processing and fabrication methods matured, the lifetime of laser diode optical pumps has increased. Tests have been performed which indicate lifetimes in excess of 10^5 hours for individual cw lasers, and greater than 10^9 pulses for pulsed laser diode arrays. A diversity of solid state laser designs are now under development to satisfy a variety of communication applications.

This paper will present an overview of the importance of the laser source to the functionality and design of a laser communication system and present recent performance results for semiconductor and solid state laser sources, specifically developed for free-space laser communication applications.

BIOGRAPHY

David L. Begley was born in Hannibal, Missouri in 1951. He received his B.S., M.S., and Ph. D. degrees in electrical engineering from the University of Missouri-Rolla in 1973, 1976, and 1978 respectively. He is currently Senior Program manager and Head-Laser Technology and Applications at Ball Aerospace System Group, Boulder, Colorado, where he directs technology and program development activities for laser communication and other laser-based systems. He was previously Senior Technical Specialist for Lasercom programs and electro-optical technology at McDonnell Douglas Astronautics Company, St. Louis division. There he managed semiconductor laser diode technology and application activities for present and future laser system. Prior to this, the was Associate Professor in the Electrical Engineering Department at Southern Illinois University-Carbondale and directed the Laser and Solid State Research Laboratories investigating applications of laser technologies to material science, metal-semiconductor interfaces and surface physics. He is cochairman of the Free-Space Laser Communications Technology Conference and editor of Milestone Series Edition, Free-Space Laser Communications. He has published or presented over nintey technical papers in solid state material science, semiconductor lasers, laser communications and laser applications.

International Workshop on
Optical Space Communication
IWOSC'90

RECENT DEVELOPMENTS IN LASER TECHNOLOGIES FOR OPTICAL SPACE COMMUNICATIONS

DAVID L. BEGLEY
BALL AEROSPACE SYSTEMS GROUP

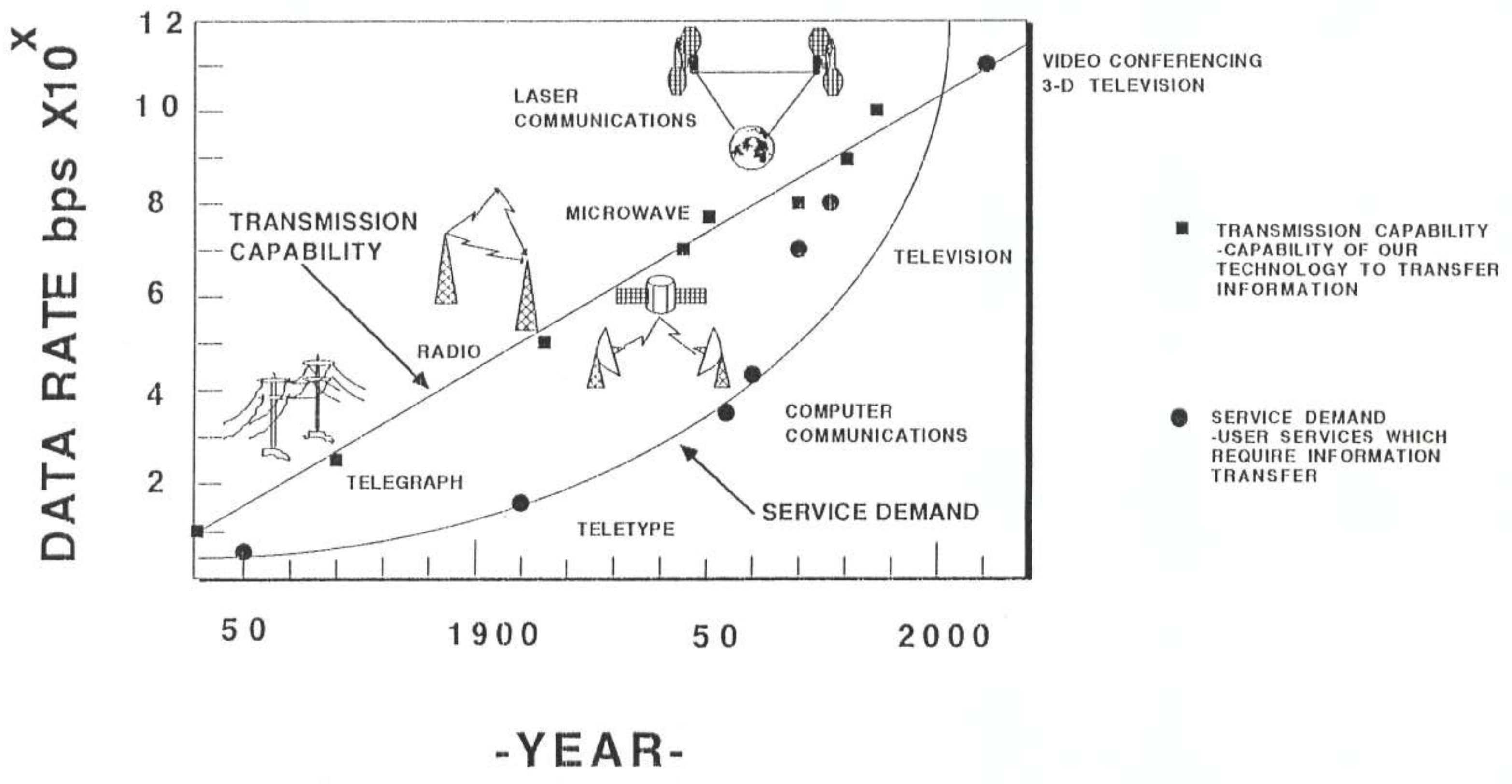
7 DECEMBER 1990

OUTLINE

- INTRODUCTION
- SEMICONDUCTOR LASER SOURCES
    - ORTEL - BURIED HETEROSTRUCTURE WINDOW
    - TRW - PHASE LOCKED ANTIGUIDE ARRAYS
    - MDESC - COHERENT ARRAY AMPLIFIER
- OPTICAL PUMP ARRAYS - LAWRENCE LIVERMORE
- SOLID STATE LASER SOURCES
    - OVERVIEW
    - DONIER - END PUMPED OSCILLATOR/AMPLIFIER
    - MDESC - SIDE PUMPED SLAB AND ROD
    - LIGHTWAVE - MONOLITHIC NONPLANAR RING
    - FIBERTEK - SIDE PUMPED ROD
- CONCLUDING REMARKS

INTRODUCTION

DEMAND VERSUS CAPABILITY IN COMMUNICATIONS



LINK EQUATION DEFINES LASER SOURCE REQUIREMENTS

$$P_R = \enclose{circle}{P_T} G_T \; G_R \; L_{SP} L_{ABS} L_P \; L_M$$

WHERE ---

P_R = AVERAGE RECEIVED POWER IN WATTS

P_T = AVERAGE TRANSMITTER POWER IN WATTS

G_T = TRANSMIT ANTENNA GAIN

G_R = RECEIVE ANTENNA GAIN

L_{SP} = FREE-SPACE PROPAGATION LOSS

L_{ABS} = ABSORPTION LOSS IN TRANSMIT AND RECEIVE OPTICS

L_P = POINTING LOSS

L_M = SYSTEM MARGIN LOSS

THE ANTENNA GAINS ARE:

$$G_T = \left[\frac{D_t \Pi}{\lambda}\right] \frac{g_t}{S^2}$$

$$G_R = \left[\frac{D_r \Pi}{\lambda}\right] (1 - L_{obs})$$

WHERE -

D_t AND D_r = PRILMARY MIRROR DIAMETERS

λ = WAVELENGTH

g_t = TRANSMIT ANTENNA EFFICIENCY

L_{obs} = RECEIVE TELESCOPE OBSCURATION LOSS

S = DEFOCUSING FACTOR

REQUIREMENTS OF A PRACTICAL LASERCOM SYSTEM

HIGH LASER POWER WITH HIGH STREHL RATIO

SENSITIVE RECEIVER

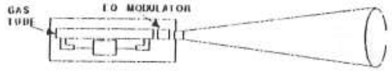
RELIABLE TRANSMITTER AND RECEIVER

IMMUNITY TO BACKGROUND, JAMMERS, TRANSMIT/RECEIVE CROSSTALK

LOW SIZE, WEIGHT, & POWER CONSUMPTION

LASER COMMUNICATIONS: A CHRONOLOGY OF THE QUEST FOR DIFFRACTION LIMITED POWER

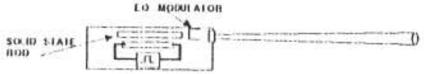
1970



CO_2

- POOR DETECTORS
- BEAM SPREAD
- SHORT LIFE

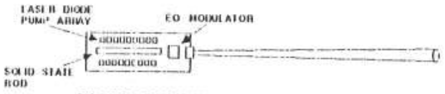
1976



LAMP PUMPED
SOLID STATE

- LOW EFFICIENCY
- SHORT LAMP LIFE

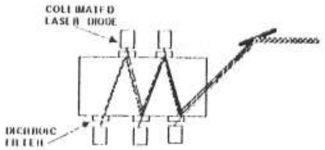
1980



DIODE PUMPED
SOLID STATE

- EXTERNAL MODULATION
- EXPENSIVE POWER

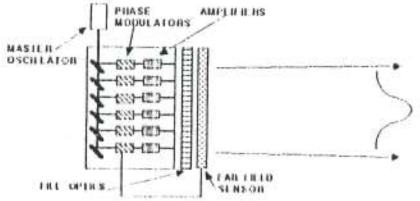
1983



DICHROICALLY
COMBINED

- LINE SHIFT CONCERNS AT HIGH POWER
- CUMULATIVE LOSSES

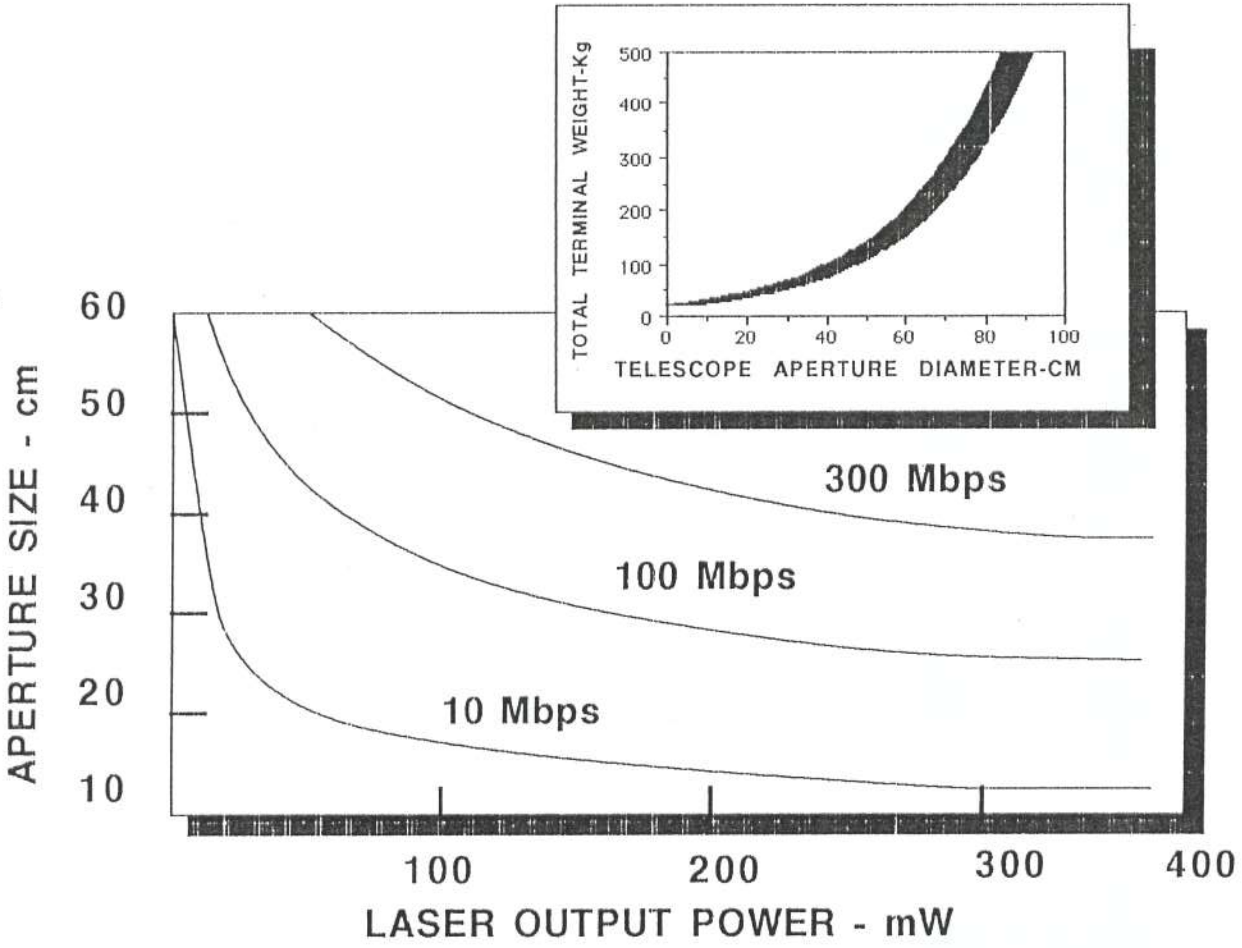
1987



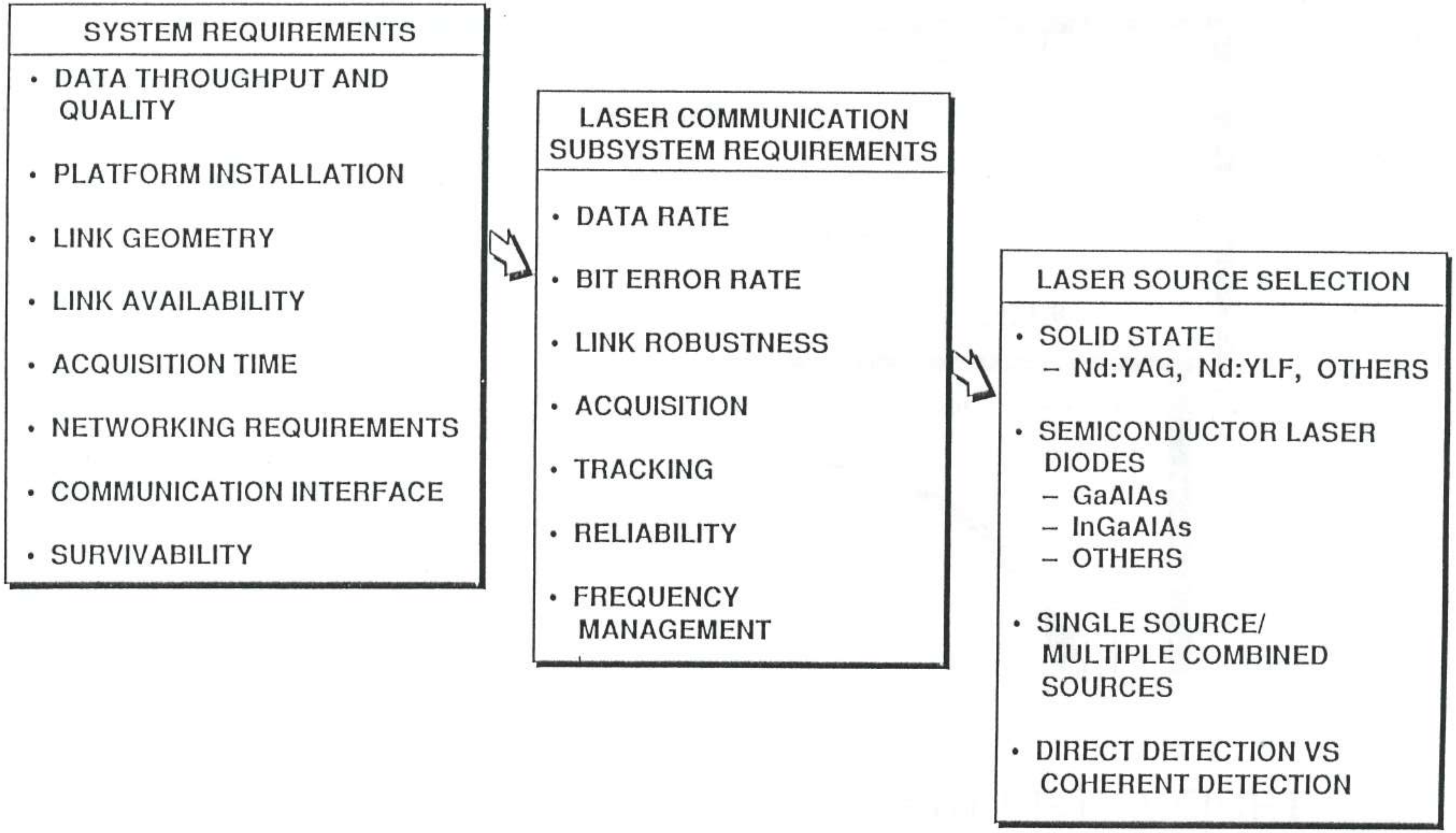
COHERENT
COMBINERS

- VERY LOW DEVICE YIELDS
- LOW RELIABILITY
- DEMANDING OPTICS
- ISOLATION PROBLEMS

LASER SOURCE PERFORMANCE LIMITATIONS ARE REFLECTED IN TERMINAL WEIGHT



LASER SOURCE SELECCTION REQUIRES A THOROUGH ASSESSMENT OF SYSTEM REQUIREMENTS



SYSTEM REQUIREMENTS

- DATA THROUGHPUT AND QUALITY
- PLATFORM INSTALLATION
- LINK GEOMETRY
- LINK AVAILABILITY
- ACQUISITION TIME
- NETWORKING REQUIREMENTS
- COMMUNICATION INTERFACE
- SURVIVABILITY

LASER COMMUNICATION SUBSYSTEM REQUIREMENTS

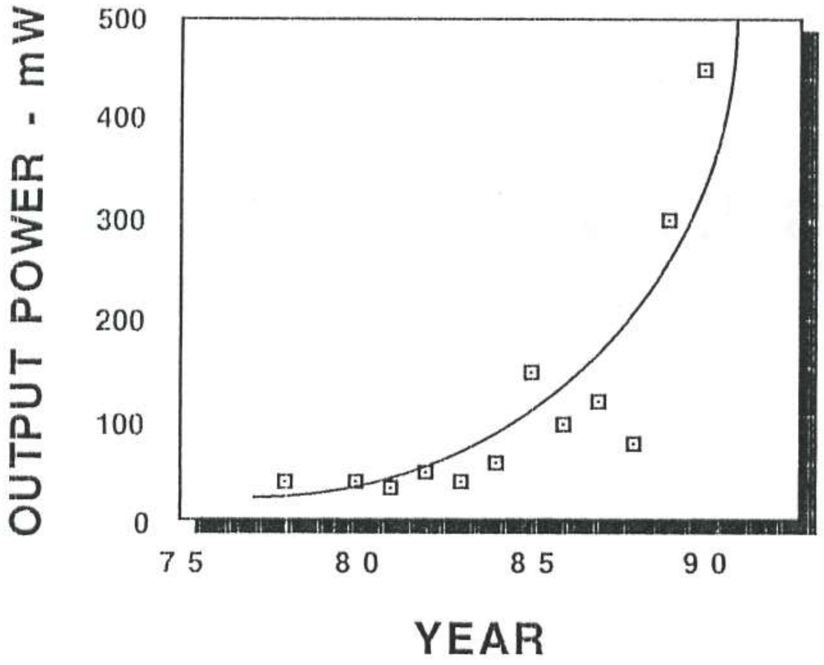
- DATA RATE
- BIT ERROR RATE
- LINK ROBUSTNESS
- ACQUISITION
- TRACKING
- RELIABILITY
- FREQUENCY MANAGEMENT

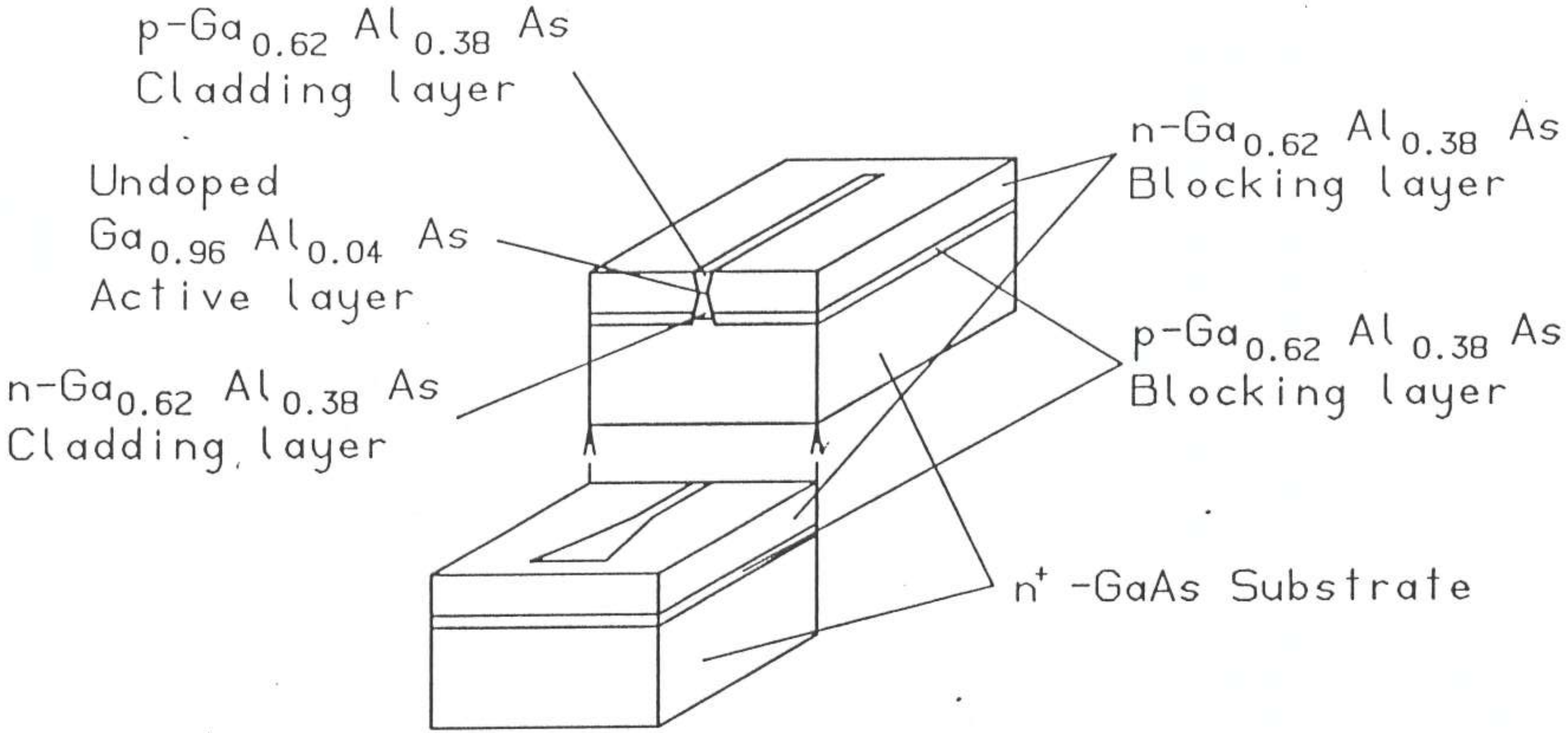
LASER SOURCE SELECTION

- SOLID STATE
  - Nd:YAG, Nd:YLF, OTHERS
- SEMICONDUCTOR LASER DIODES
  - GaAIAs
  - InGaAIAs
  - OTHERS
- SINGLE SOURCE/ MULTIPLE COMBINED SOURCES
- DIRECT DETECTION VS COHERENT DETECTION

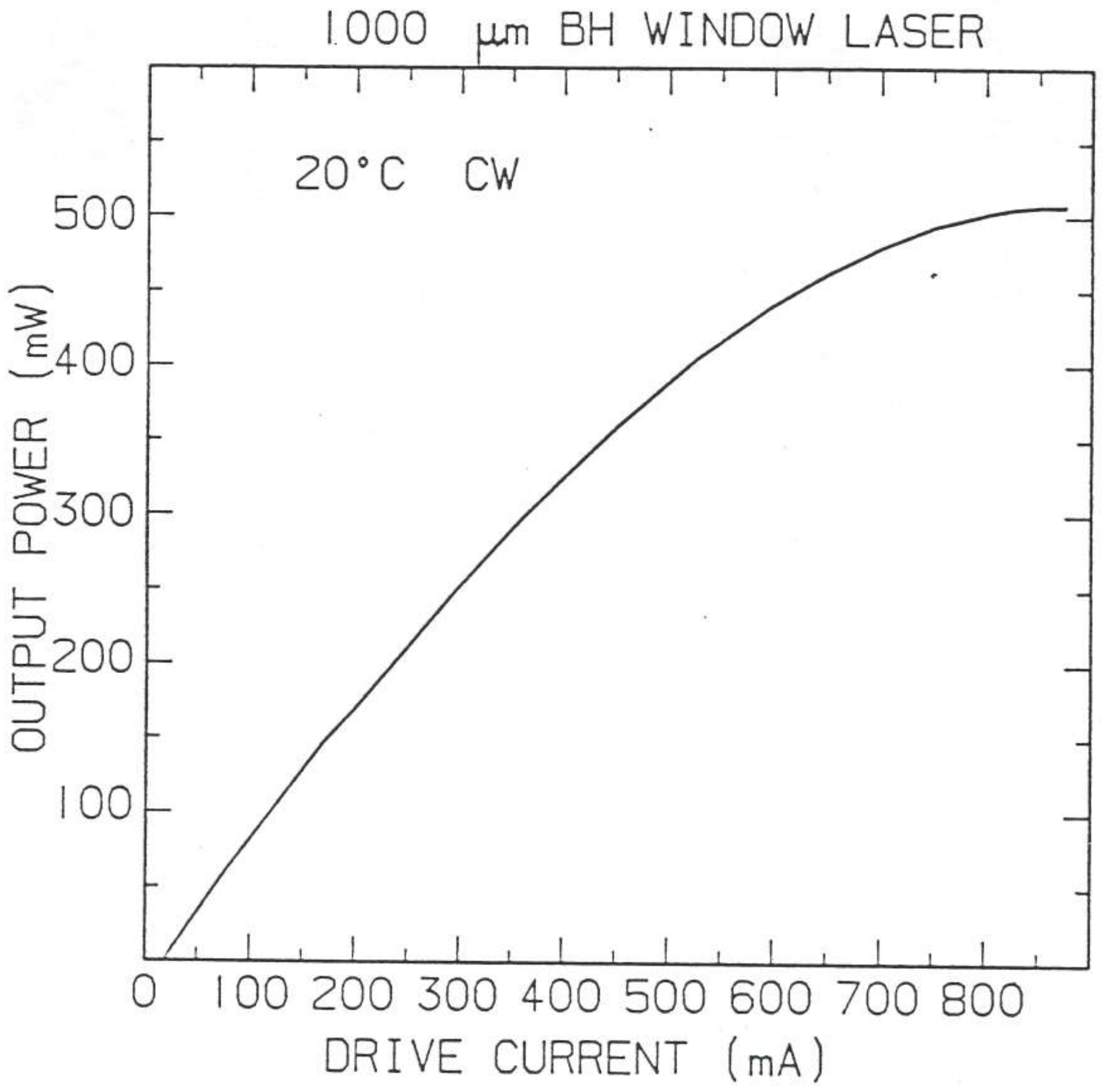
SEMICONDUCTOR LASER SOURCES

SINGLE MODE LASER POWER
INCREASES OVER LAST 10 YEARS



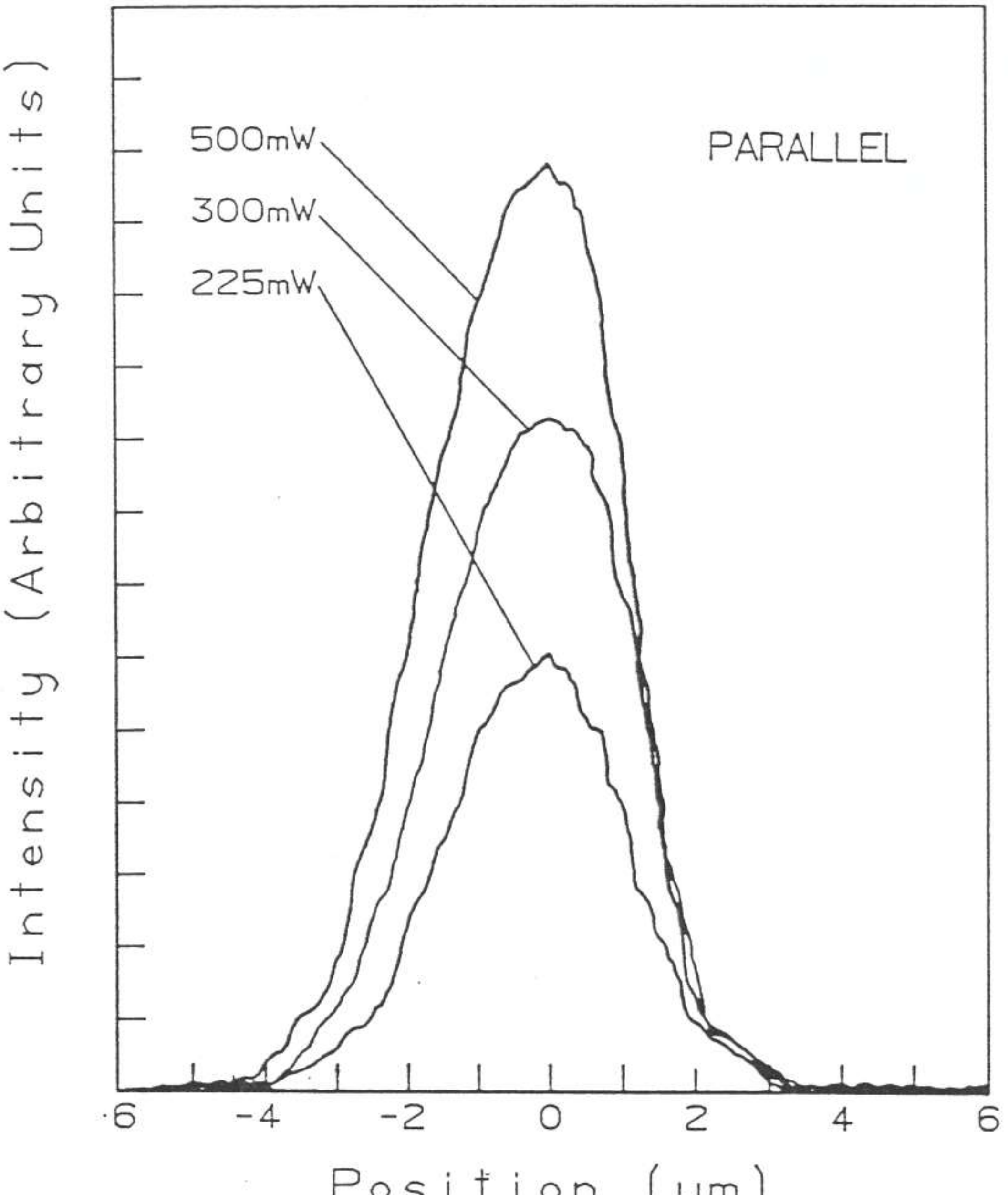


BURIED HETEROSTRUCTURE WINDOW LASER


1.000 µm BH WINDOW LASER
20°C CW
OUTPUT POWER (mW)
100
200
300
400
500
0
100
200
300
400
500
600
700
800
DRIVE CURRENT (mA)

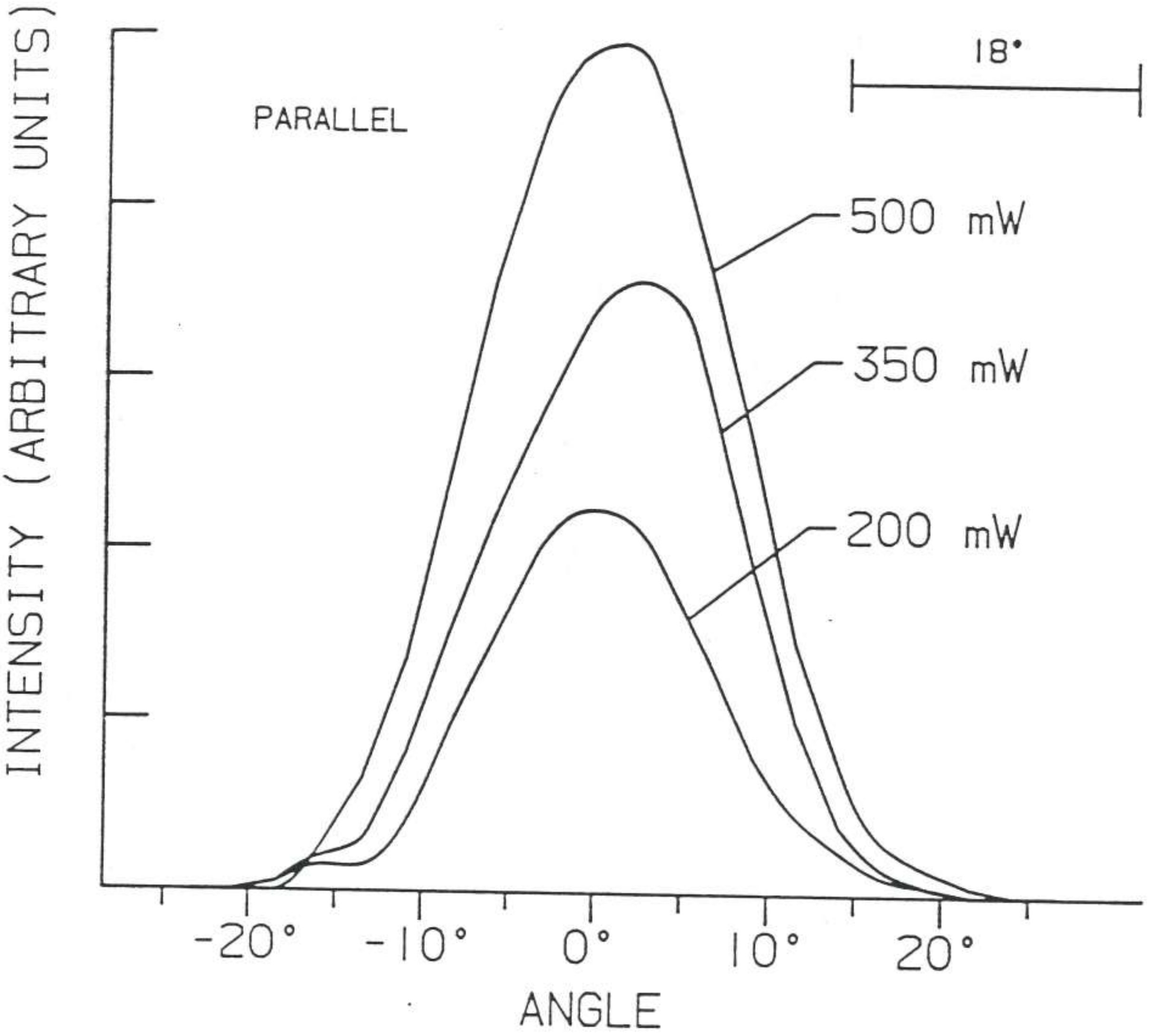
JU911012

1000 μm BH WINDOW LASER



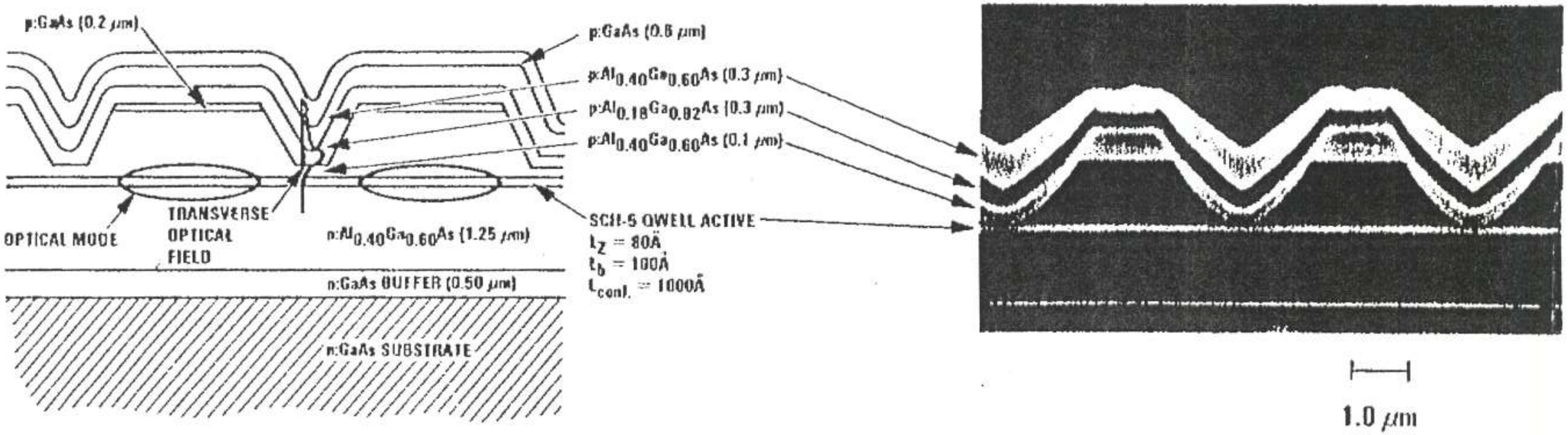
ORTEL CORPORATION

1000 µm BH WINDOW LASER



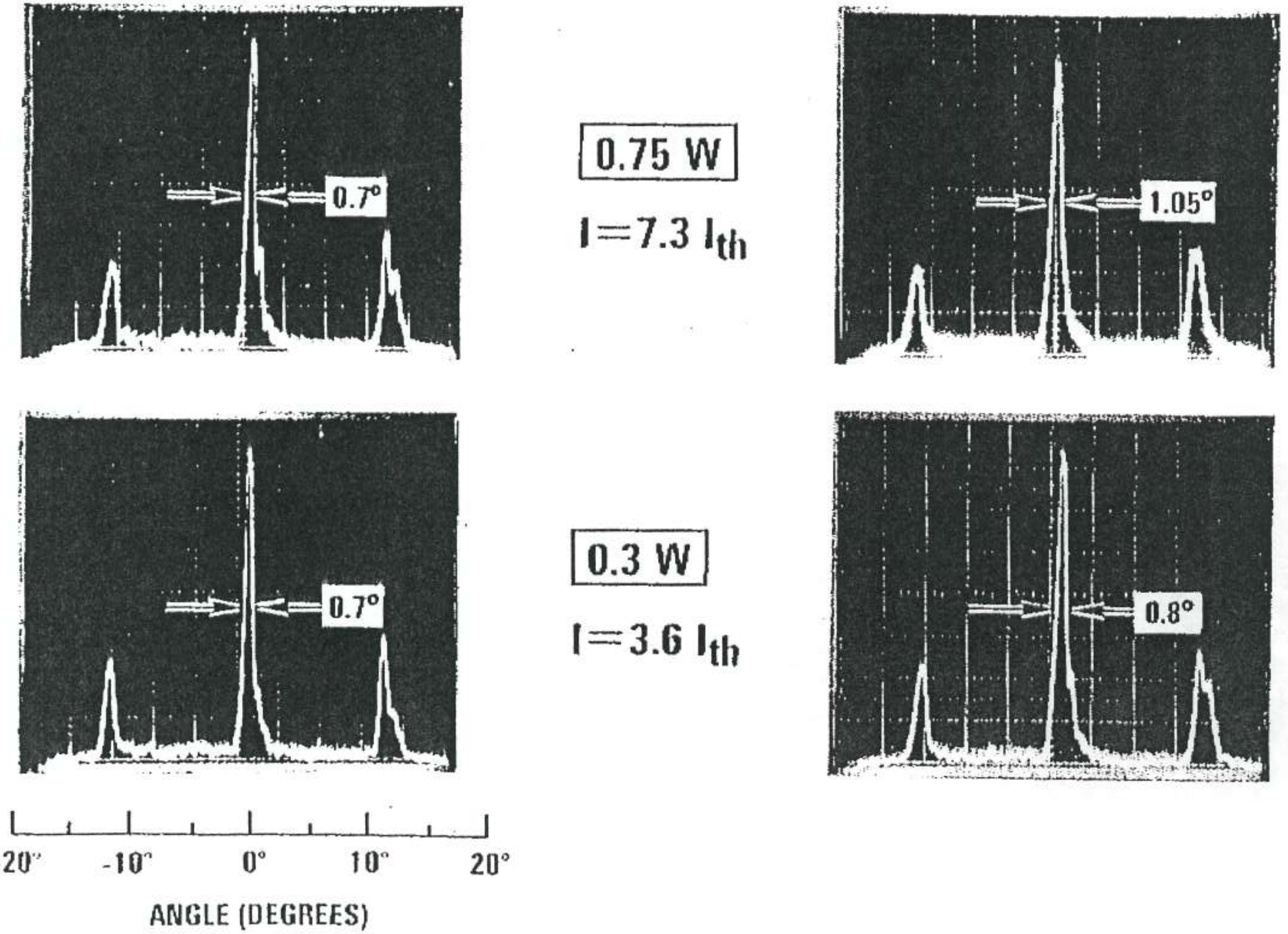
ORTEL
CORPORATION

Phase-Locked Arrays of Antiguides (Leaky-Wave Guides)



- All MOCVD-grown quantum-well structure

Beam Pattern of Optimized ROW Array*



DIFFRACTION
LIMIT H

0.75 W

$I = 7.3\ I_{th}$

2 W

$I = 19\ I_{th}$

0.3 W

$I = 3.6\ I_{th}$

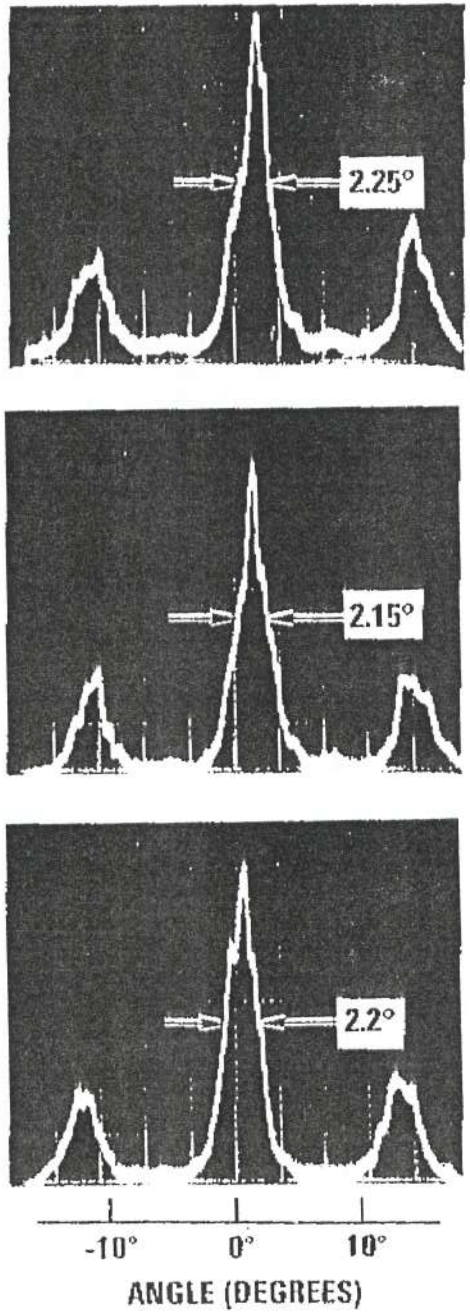
1.25 W

$I = 10.7\ I_{th}$

$I_{th} = 270$ mA
$\eta_d = 31\%$

*TWO-TALBOT DEVICES

High-Power Far-Field Patterns*



DIFFRACTION
LIMIT H

5 W

$I = 45\ I_{th}$

4 W

$I = 34\ I_{th}$

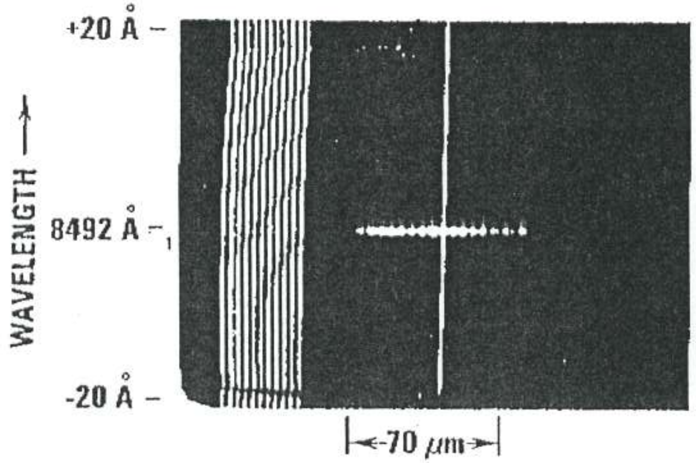
2.8 W

$I = 23\ I_{th}$

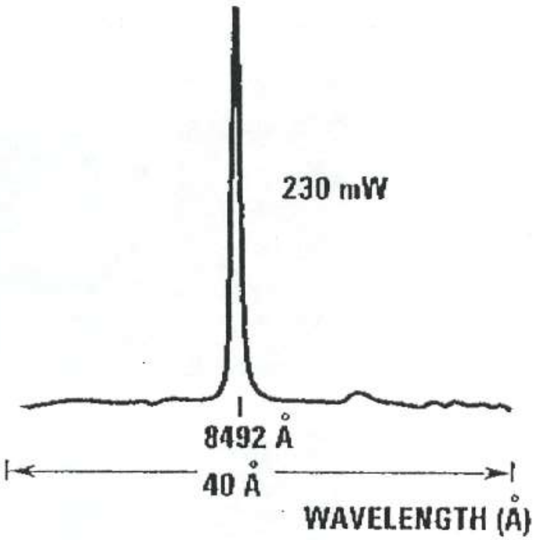
$I_{th} = 260$ mA
$\eta_d = 35\%$

*UNIFORM DEVICES

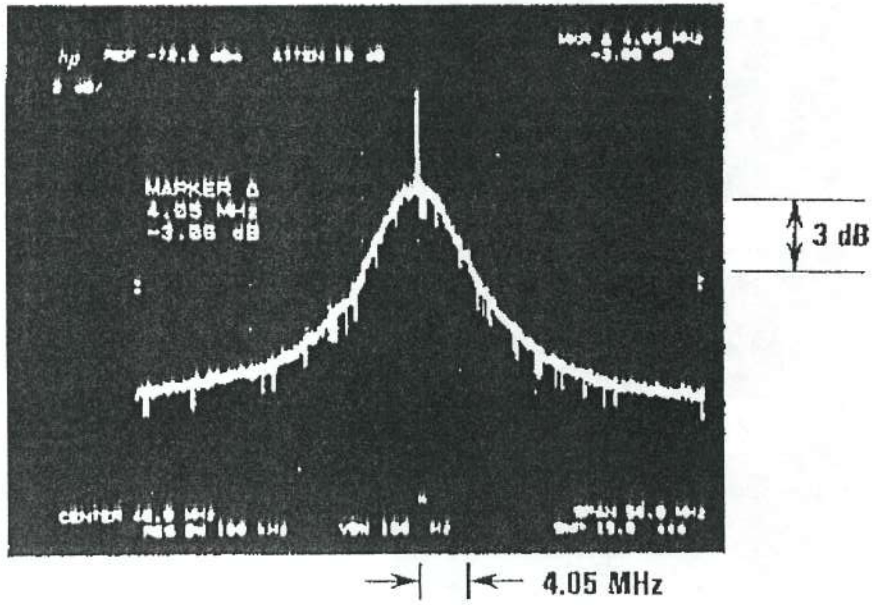
Spectral Behavior



NEAR FIELD PROFILE

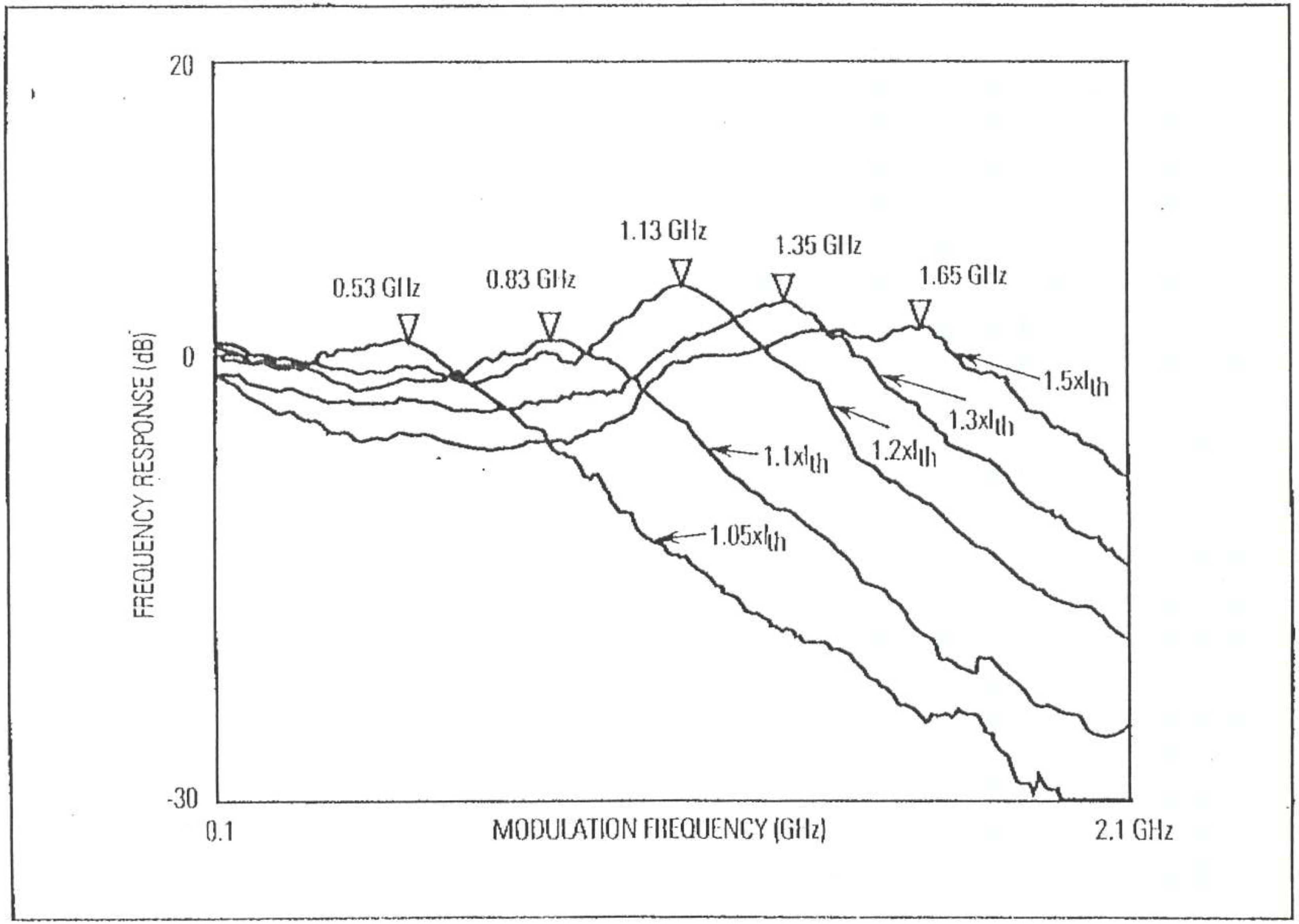


- Single-longitudinal-mode operation to 230 mW pulsed

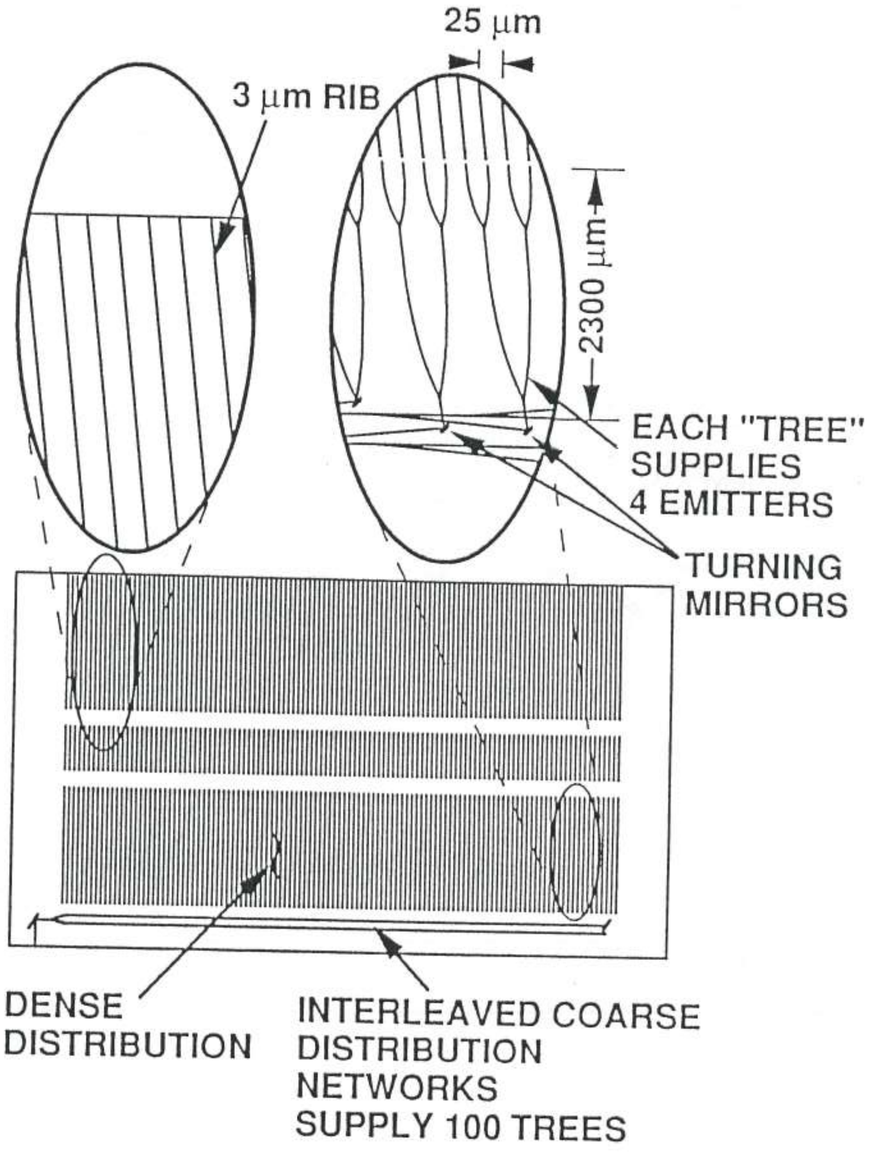


- 4 MHz linewidth (self-heterodyne RF spectrum-analyzer trace)

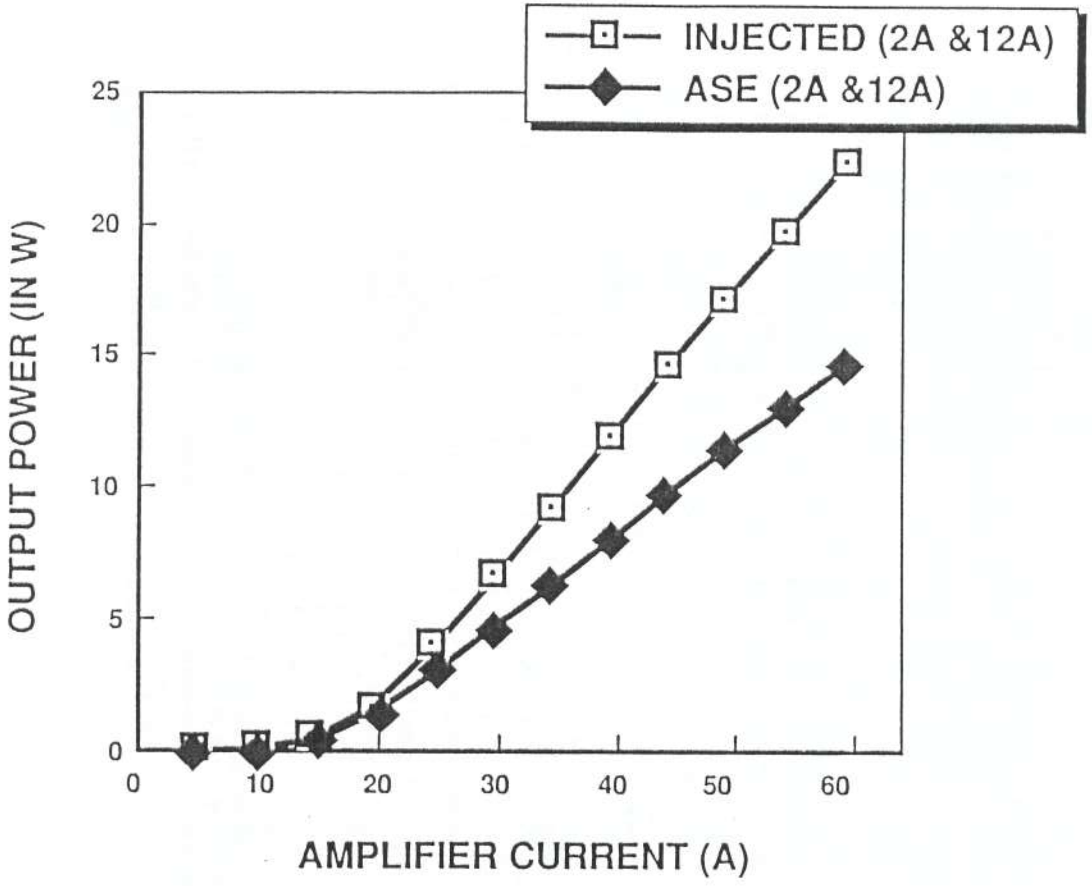
MODULATION RESPONSE OF ROW ARRAYS



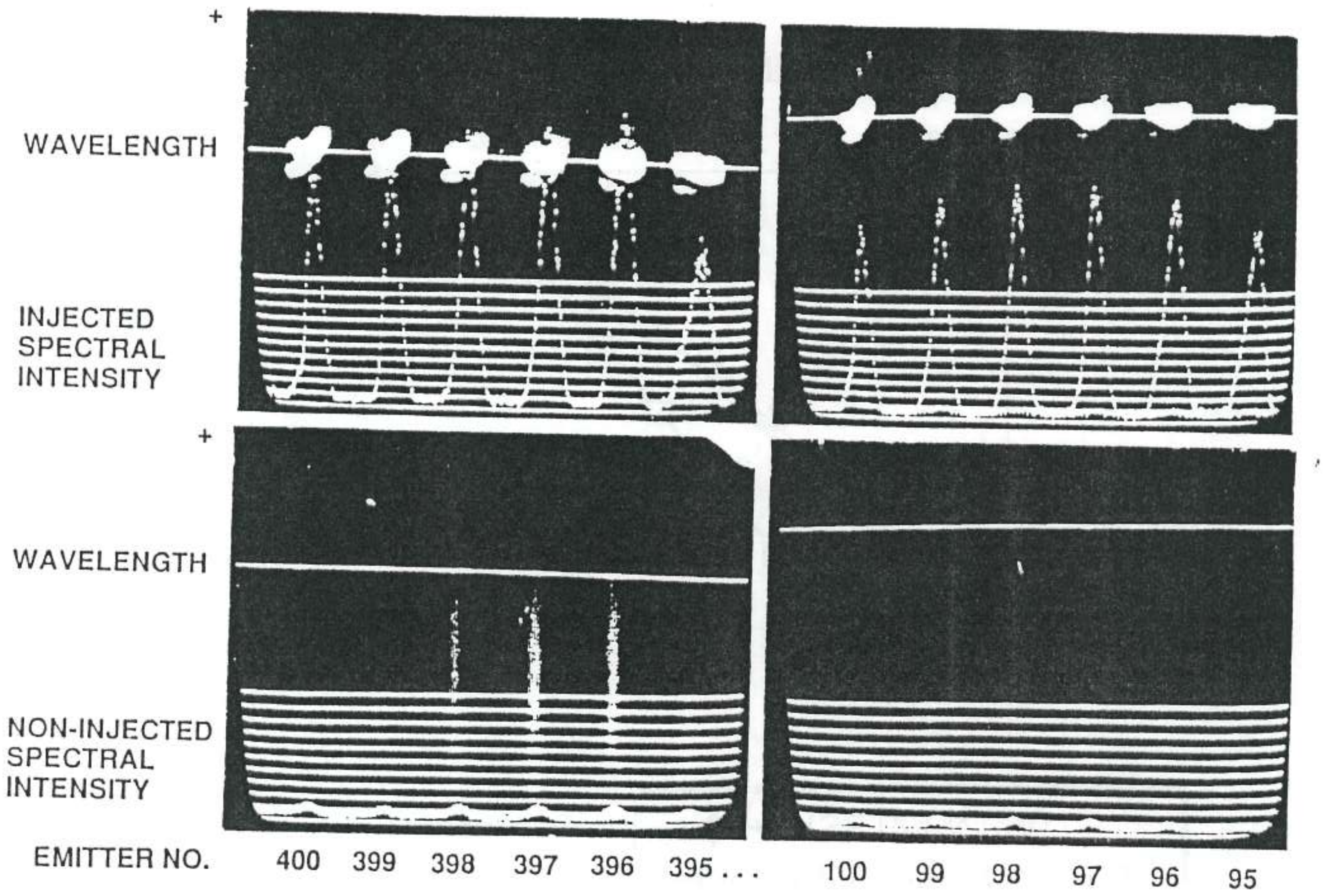
BASIC LAYOUT OF 400-EMITTER COHERENT AMPLIFIER CHIP



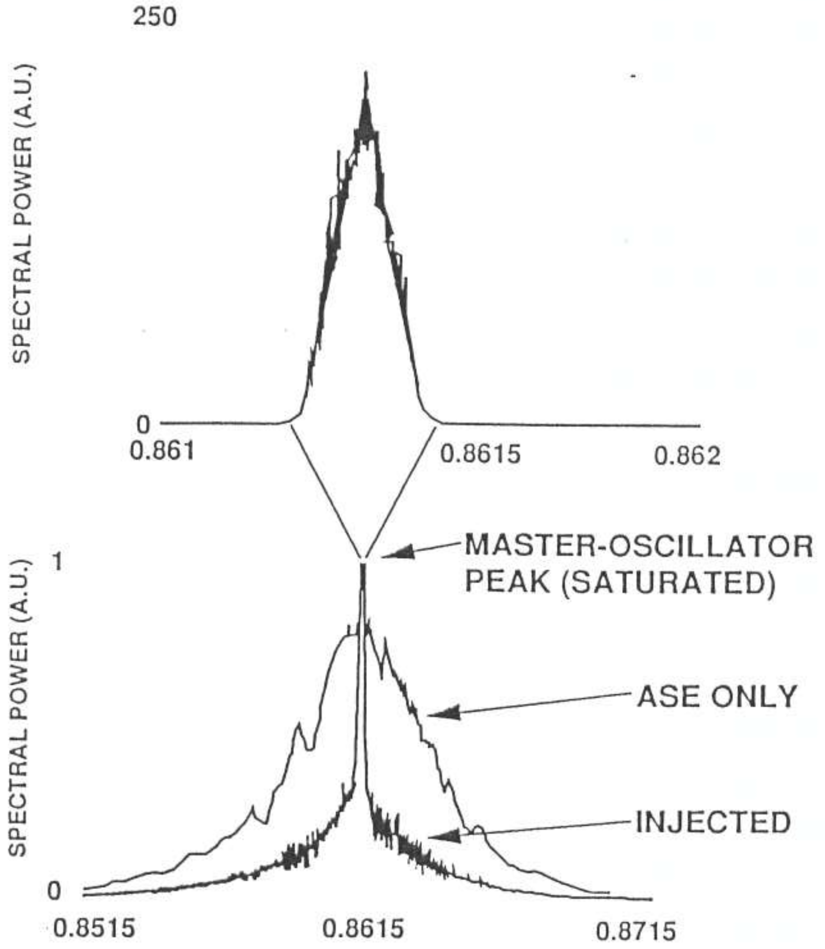
PEAK OUTPUT POWER VERSUS CURRENT TO POWER AMPLIFIERS



SPECTRALLY RESOLVED LATERAL NEAR FIELD



SPECTRAL SCAN OF WAVEGUIDE EMISSION



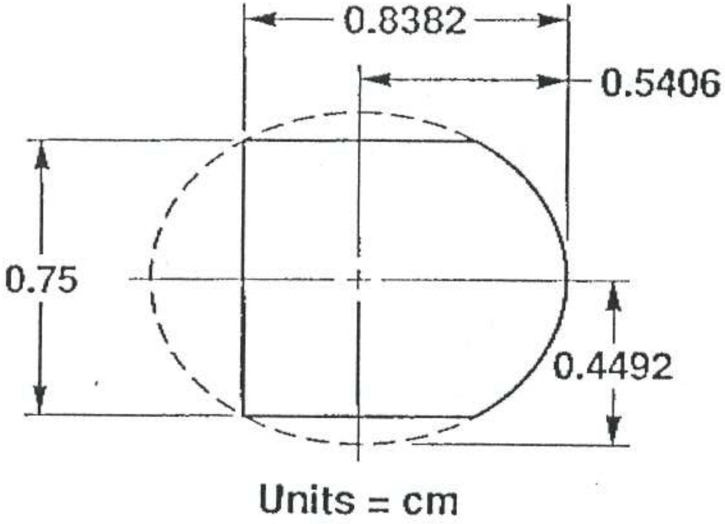
OPTICAL PUMP ARRAYS

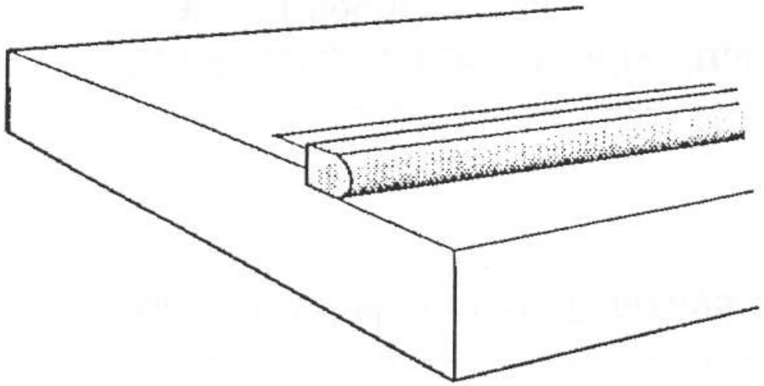
Currently available laser diode arrays are not optimized pump sources for solid state lasers

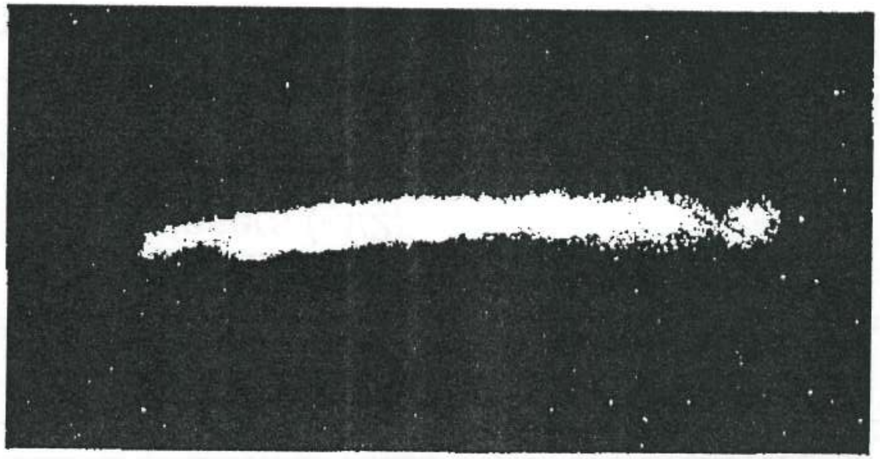
Issues	Potential solutions
• Large beam divergence perpendicular to junction places severe constraint on coupling optics (~f/1)	• Integrated quantum well manifold lasers (~f/2)
• Array linewidths generally too large to ensure good coupling to solid state laser crystals	• Injection locked 2D arrays
• High prf, large aperture solid state lasers require cw 2D pump arrays with ~100-400 W/cm² optical irradiance	• Microchannel cooled 2D arrays
• Pump induced gain uniformity and variation with time needs to be quantified	• Small scale control of individual 2D array subsections
• $1000/cw watt or $100/peak watt → $	• Manufacturing technology to improve yield → ¢

AA-DPSSL-0889-239

Large numerical aperture fiber lens are efficient and economical to produce







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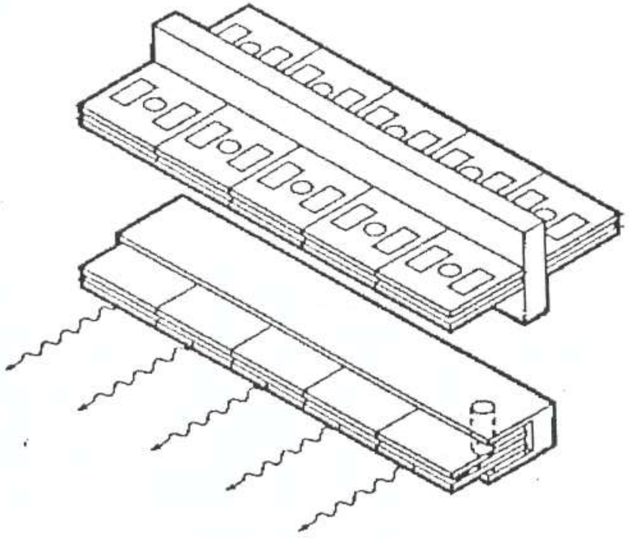
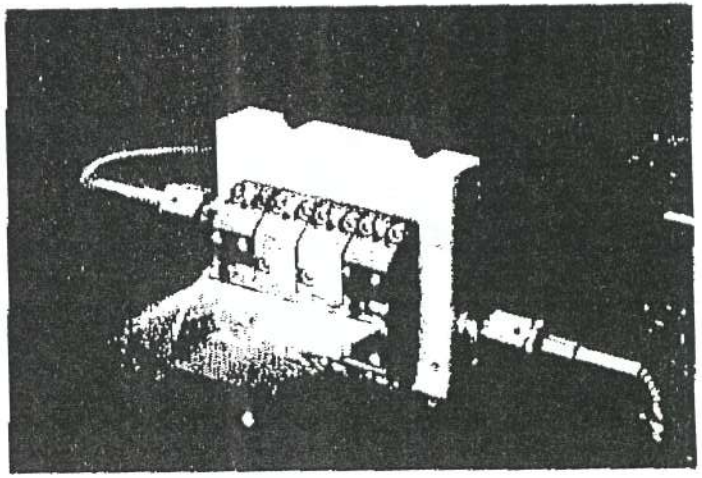
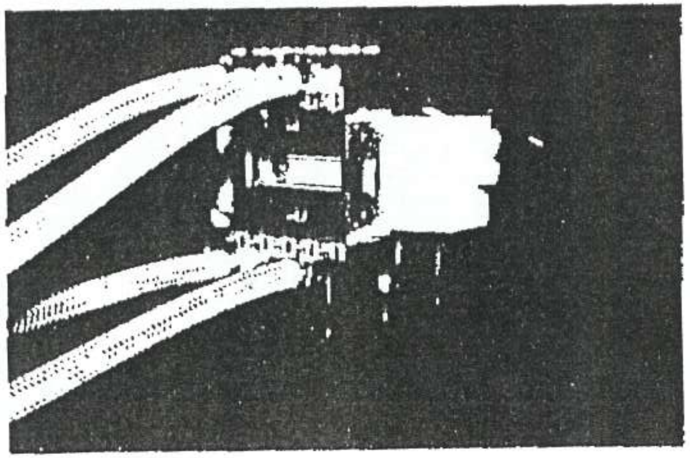
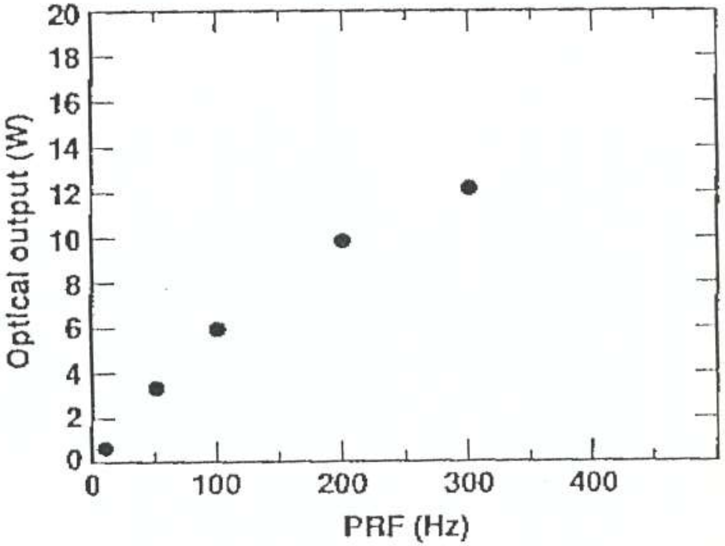
MX-029-U-12489 F 4

High power diode pumped solid state laser test bed



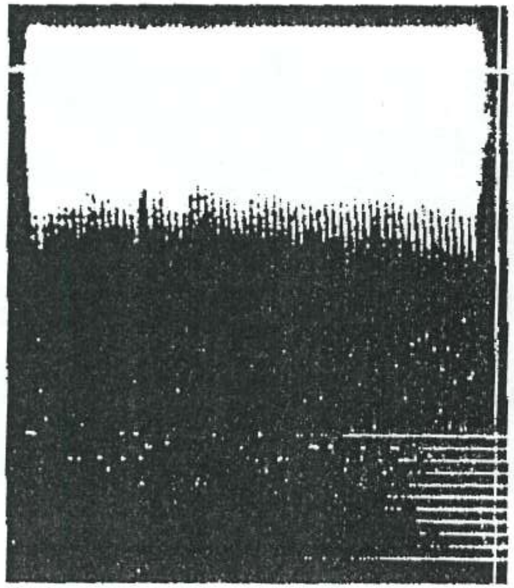




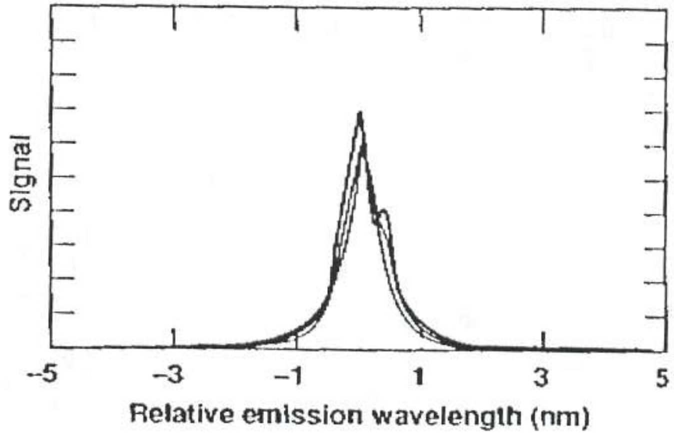


Typical diode package performance parameters

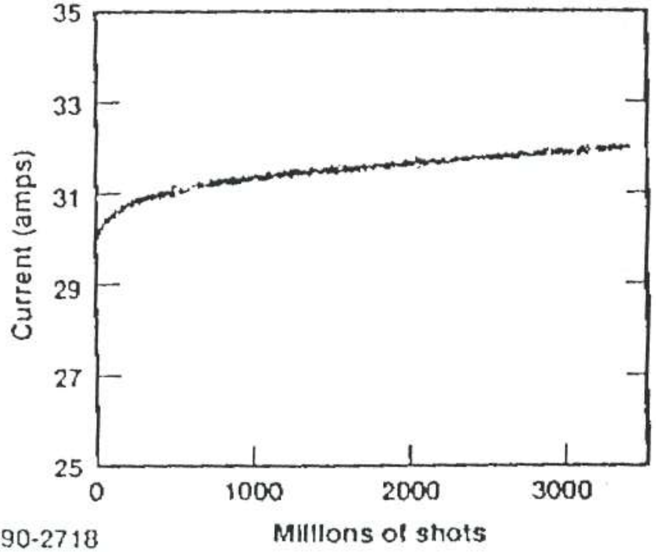
intensity uniformity



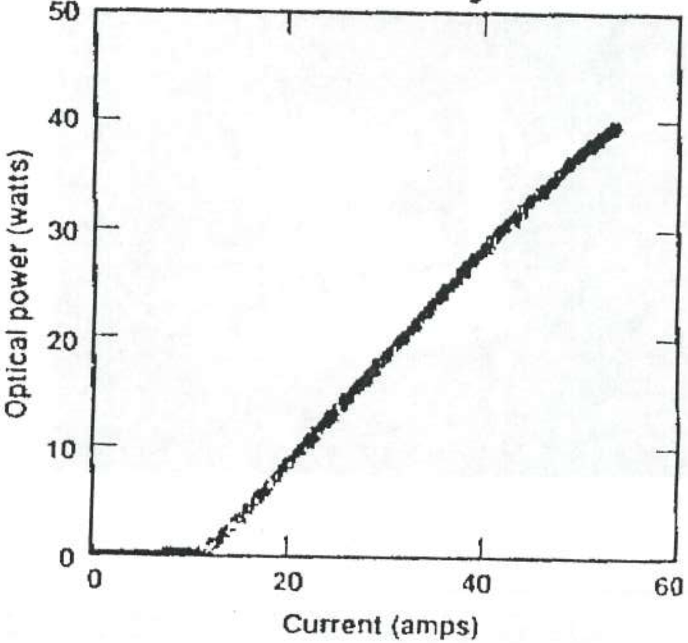
wavelength uniformity



lifetime



efficiency



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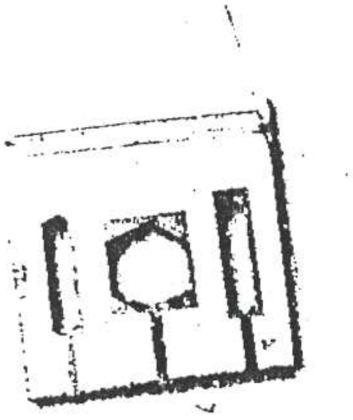
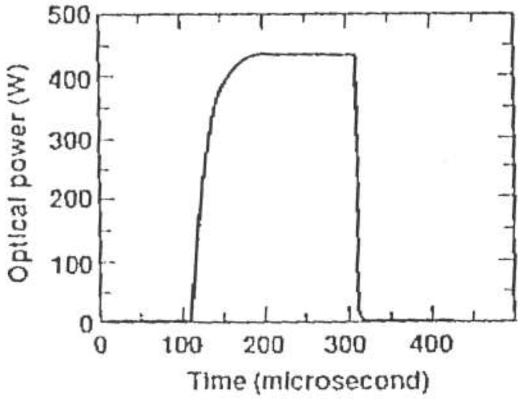
MX-030-U-12499/F 6

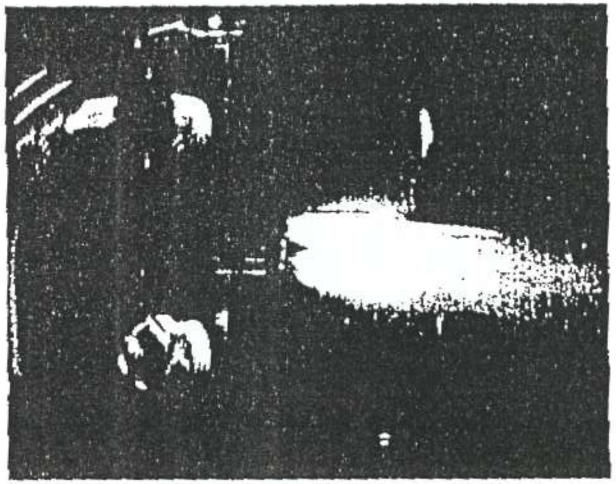
Compact, high intensity and high average power optical pump sources for solid state lasers



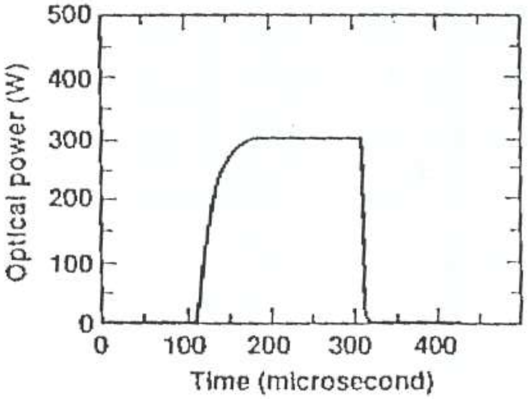
Basic unit
- Wafer thin
- Stackable
- Low thermal impedance



Low duty factor optical output
140 amps @ 10 Hz



Compact, high power, pump array
5 basic units stacked together
Series electrical – cooled in parallel



High duty factor optical output
130 amps @ 2.5 kHz
Average optical power 80 W/cm^2

85-35-0790-2578 A
RXS U 11916 SWS 2578

6/90

Significant progress has been made in packaging high average power laser diode arrays

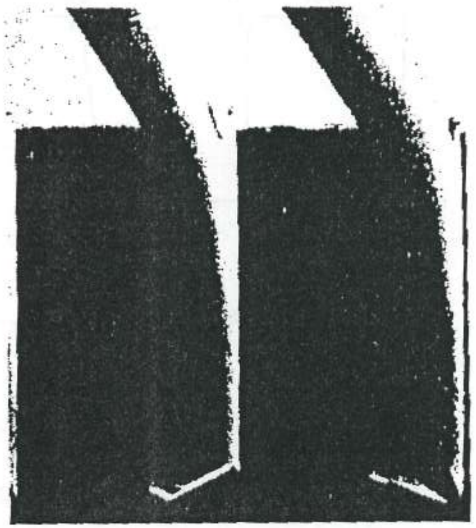
Silicon microchannels integrated with laser diode arrays are the packaging approach of choice:

- Extremely low thermal resistance can be achieved over large areas with a negligible investment of coolant pump power. Thermal impedance of less than 0.025°C/(W/cm^2) can be obtained
- Temperature uniformity can be maintained over large areas

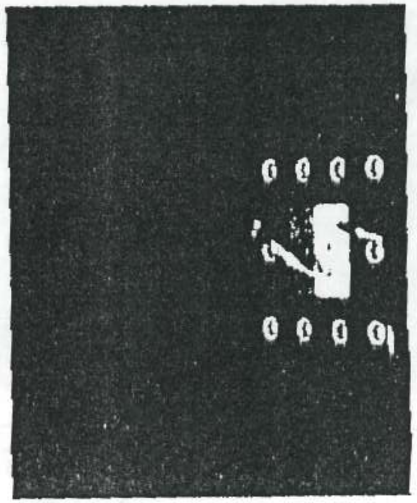
  $\Delta T = 1°C/(kW/cm^2)$ at a coolant pump power
  $= 8\%$ of waste heat flux

- They are compact, inexpensive, (projected to be ≈ \$32/cm^2) and easily adapted and optimized for different architectures including monolithic, surface emitters and "rack and stack" designs

Etched microchannels



Integrated laser diode array — cooler assembly



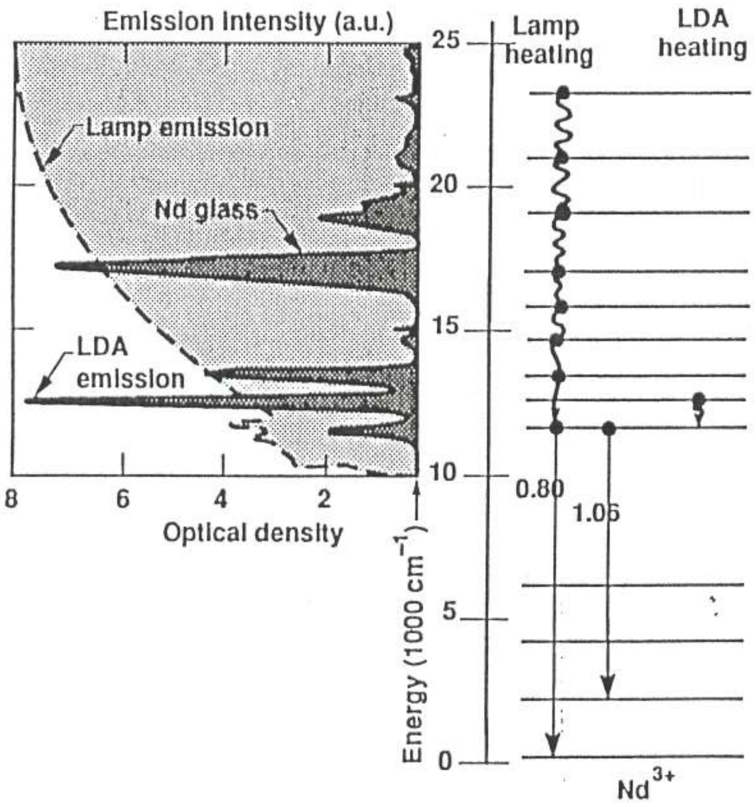
SOLID STATE LASER SOURCES

Nd^{3+} LASER HOST MATERIALS*

HOST MATERIAL	CHEMICAL FORMULA	ACHRONYM	FLUORESCENCE LIFETIME-µsec	PEAK LASER CROSS SECTION $X10^{-19}$ cm^2	THERMAL CONDUCTIVITY $Wcm^{-1}K^{-1}$	LASING WAVELENGTH µmeters
Yttrium Aluminum Garnet	$Y_3Al_5O_{12}$	YAG	230	4.6	0.13	1.064
Yttrium Orthoaluminate	$YAlO_3$	YALO	180	1, 1.8	—	1.078,1.065
Yttrium Lanthanum Fluoride	$YLiF_4$	YLF	520	1.8, 1.2	0.06	1.053,1.047
Lanthanum Beryllate	$La_2Be_2O_5$	BEL	150	2.1	0.046	1.080,1.070
Calcium Fluorophosphate	$Ca_5(PO_4)_3F$	FAP	240	5.0	0.02	1.063
Gadolinium Scandium Aluminum Garnet	$Gd_3Sc_2Al_3O_{12}$	GADSCAG	250	3.2	—	1.060
Gadolinium Gallium Garnet	$Gd_3Ga_5O_{12}$	GGG	260	1.2	—	1.060
Barium Magnesium Germanate Garnet	$Ba_{.25}Mg_{2.75}Y_2Ge_3O_{12}$	BAMGAR	310	0.6	0.06	1.062

Average or representative values (actual values will depend on particular doping levels and other properties).

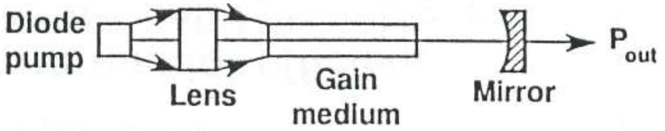
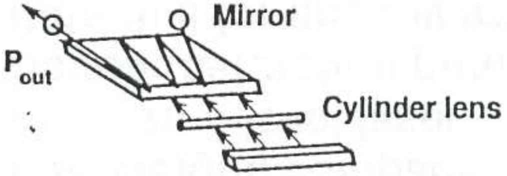
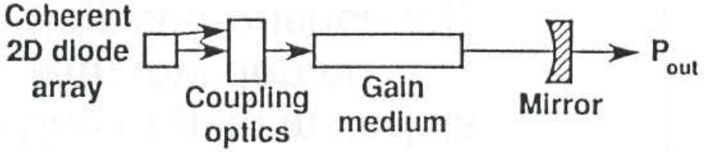
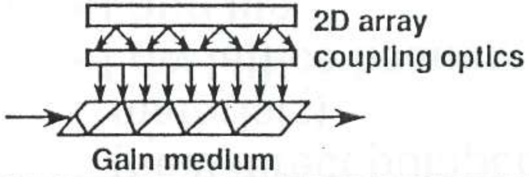
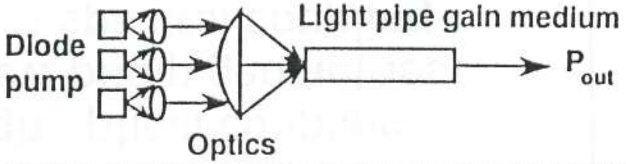
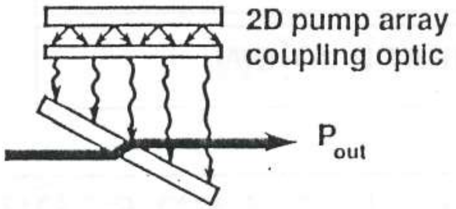
LDAs have significant advantages as laser pumps



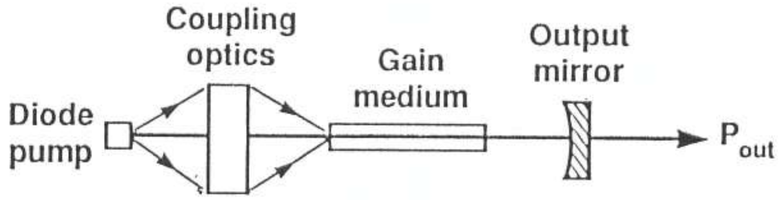
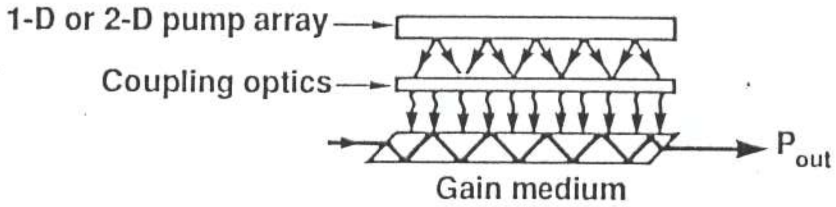
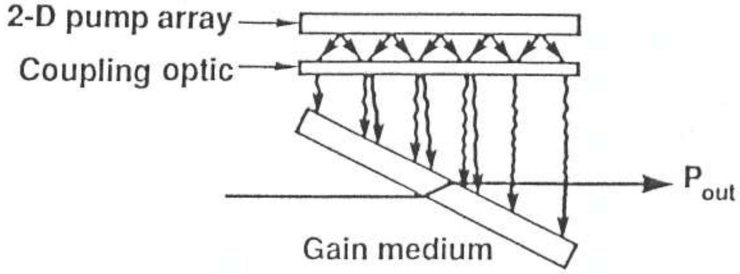
Major advantages

- High optical coupling (new pump geometries)
- High spectral coupling (new direct pumped gain materials)
- Low lattice heating
- Long life
- Use of gain materials with low doping (low self-quenching)
- Low weight, compact
- Efficient 3-level laser action (saturation pumping)
- Potential for upconversion pumping
- Potential for efficient mid-IR solid state lasers

Semiconductor laser pumping geometries

TEM_{00} power regime	Pump/gain-medium configuration (schematic)	
P_{out} ~ 10's of watts	Incoherent end pumped rod oscillator	
	Edge pumped zig-zag	
P_{out} ~ 100's of watts	Coherent end pumped rod	
	Face pumped zig-zag	
	Incoherent end pumped regen amplifier	
P_{out} > 1000 of watts	Side pumped Brewster plate	

Single-aperture power scaling and associated geometries

TEM_{00} power regime	Pump/gain-medium configuration (schematic)
$P_{out} \lesssim 10$ watts	End-pumped rod 
$P_{out} \lesssim 1000$ watts	Side-pump zig-zag slab 
$P_{out} > 1000$ watts	Side-pumped Brewster plate 

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DIODE PUMPED Nd:YAG LASER
RESULTS COMPARISON

PARAMETER	END PUMPED ROD		SIDE PUMPED ROD		SLAB		NONPLANAR RING	
	SPACE QUAL	LAB	SPACE QUAL.	LAB	SPACE QUAL.	LAB	SPACE QUAL.	LAB
INPUT POWER TO PUMP-W	1.8	15	33	70	10,340	10,000	- -	8.0
OUTPUT POWER FROM PUMP-W	0.4	1.9	4.5	15	3,960	2,400	- -	1.98
OUTPUT POWER FROM LASER-W	0.13	0.66	1.0	1.9	- -	- -	- -	0.9
OUTPUT ENERGY FROM LASER-mJ	- -	- -	- -	- -	>50	170	- -	- -
OPTICAL CONVERSION EFFICIENCY-%	32	34	22	12.7	8.4	26	- -	46
TOTAL LASER EFFICIENCY-%	7	4.4	3	2.7	3.2	6	- -	11.3

European Space Agency (ESA)
1 W CW diode pumped Nd:YAG transmitter laser breadboard for coherent space communications

(developed by DORNIER, ADLAS, SIEMENS in Germany)

Configuration:

High power single mode oscillator, non-resonant amplifier

Oscillator:

Single end pumped twisted-mode linear discrete resonator pumped by two polarization coupled 1 W diodes

Amplifier:

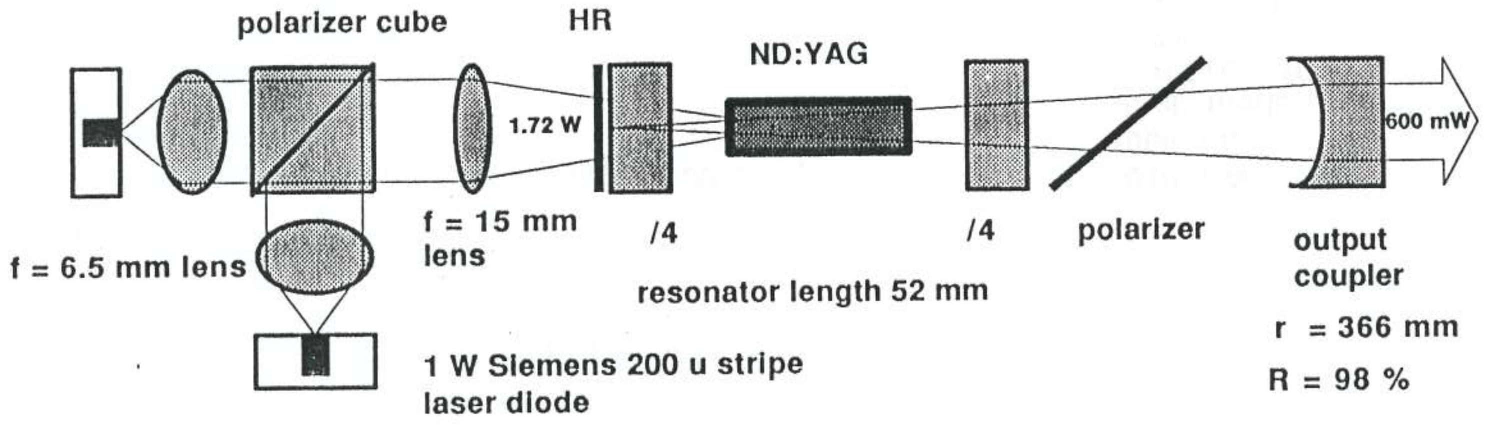
Three stage end pumped double-pass rod amplifier each stage pumped by one 1 W diode

Measured performance:

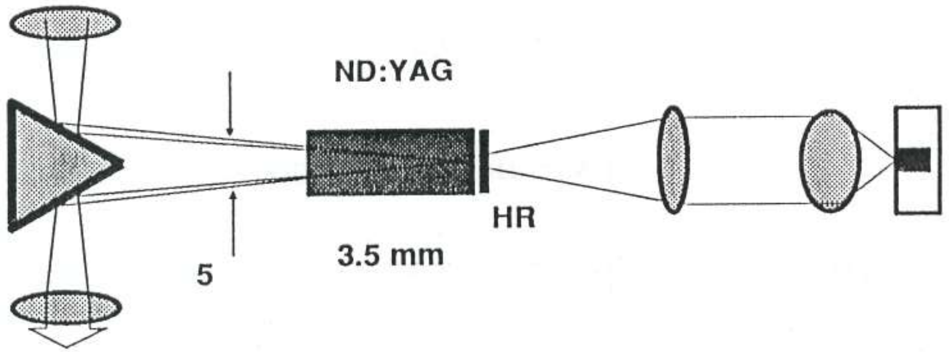
output power (diodes operated at 900 mW)	1010 mW
wavelength	1064 nm
spectral quality	single mode
linewidth	< 20 kHz / 10 ms
frequency stability	< 600 kHz / min
spatial quality	diffraction limited TEM00
effective waist	226 um (h), 277 um (v)
beam wandering	< 10 % divergence
polarization	1 : TBD linear
electrical to optical conversion efficiency	6.3 %

UJ-291090-1

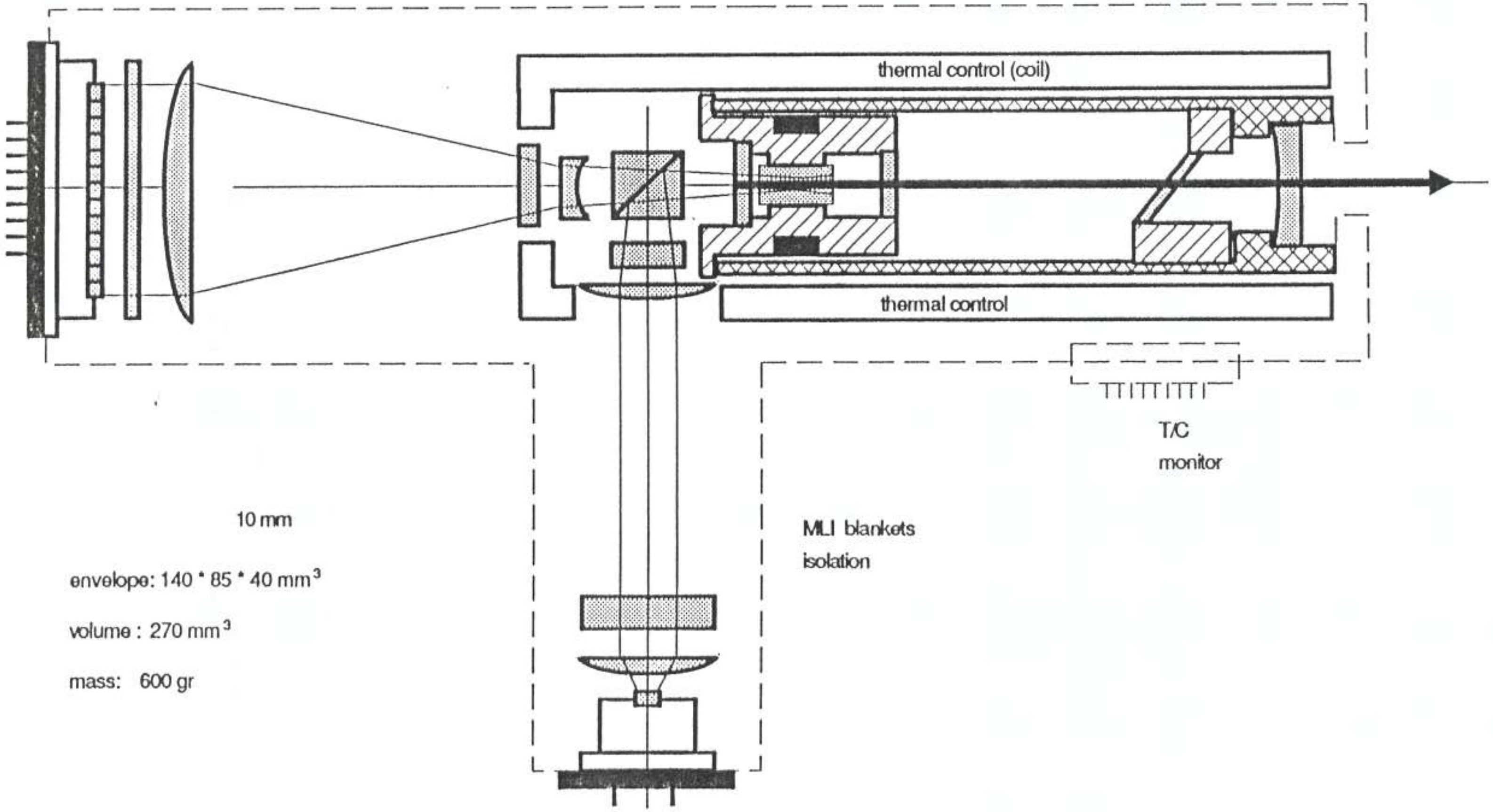
End pumped twisted mode linear discrete resonator



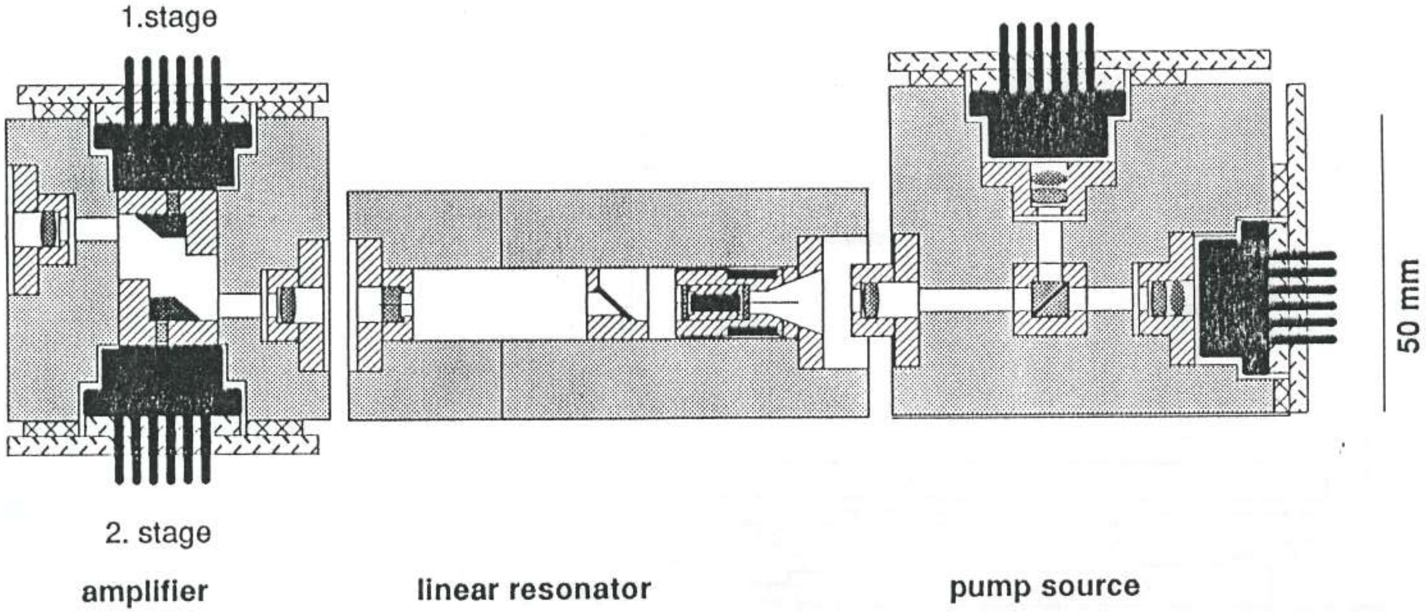
Two pass end pumped non resonant amplifier



Schematic diagrams of oscillator and amplifier

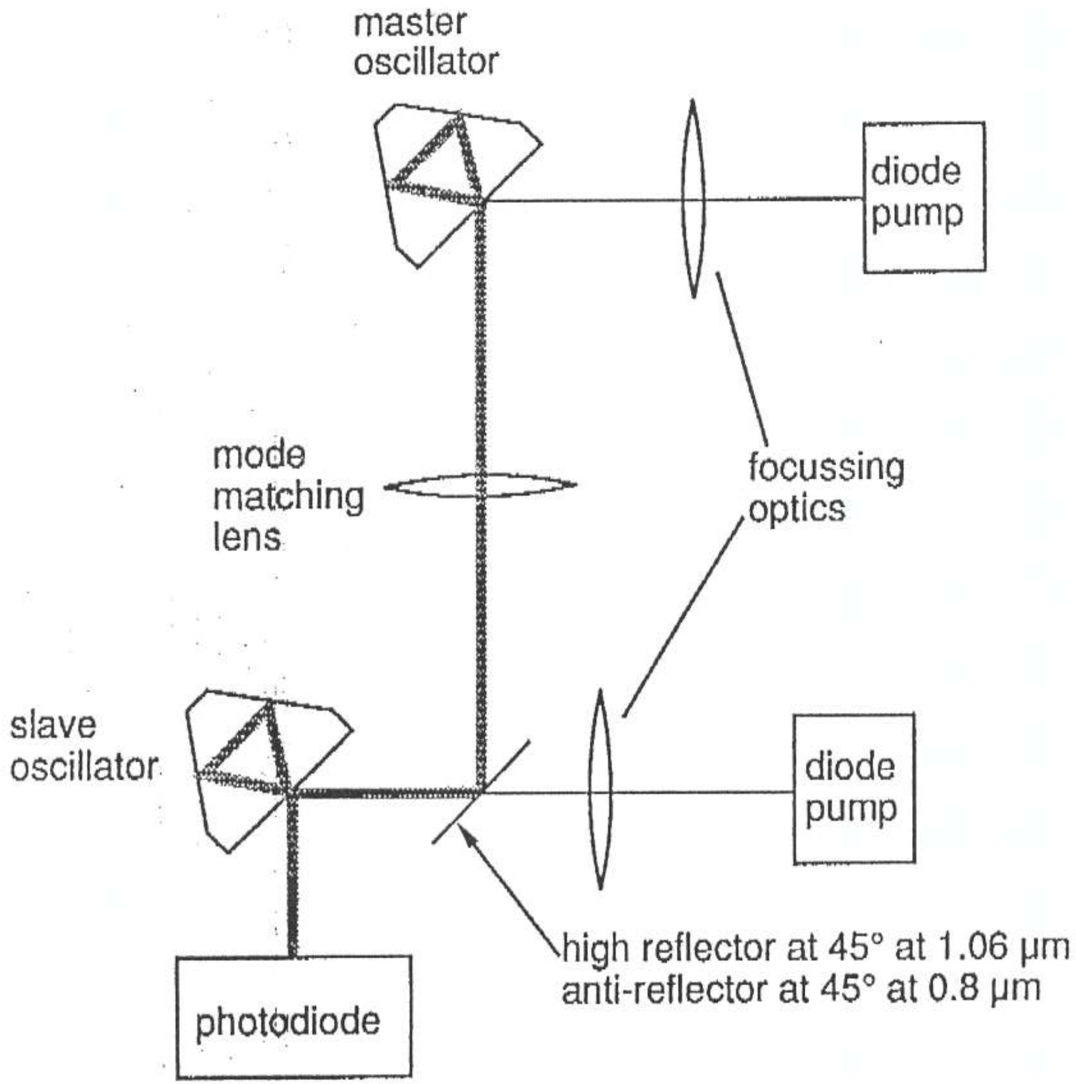


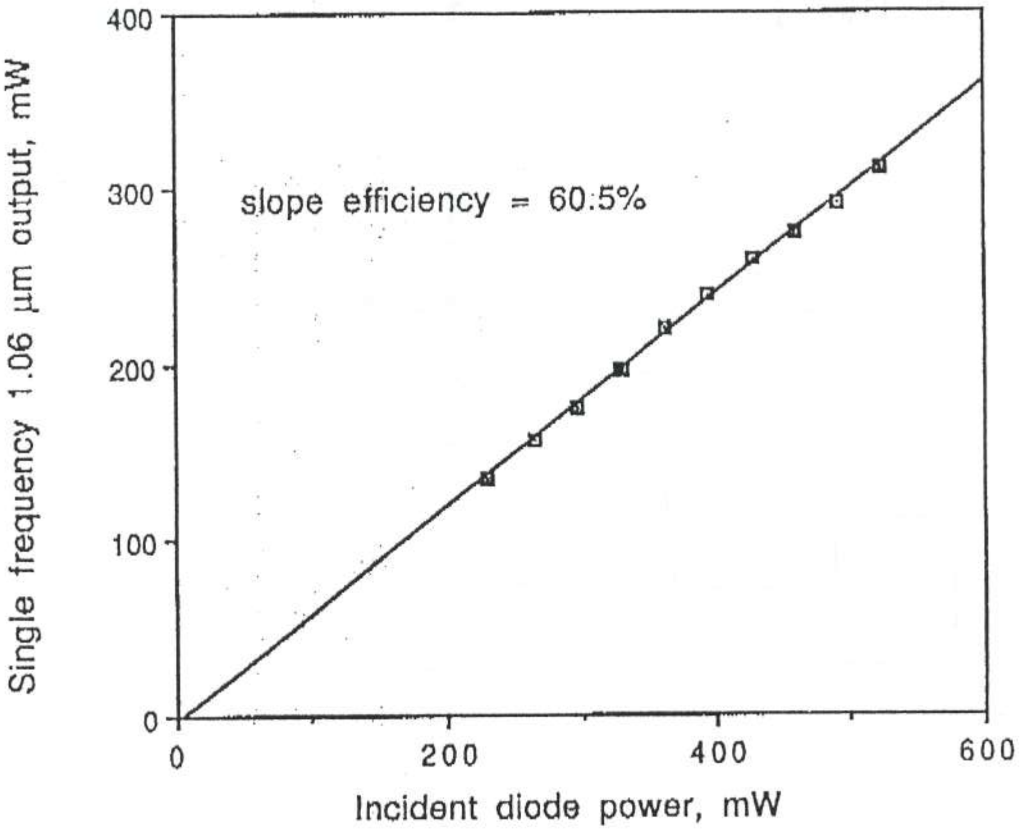
Conceptual space design of laser oscillator
fully redundant pump source with 2 sets of 12 stacked laser diodes (asticmatic focussing)

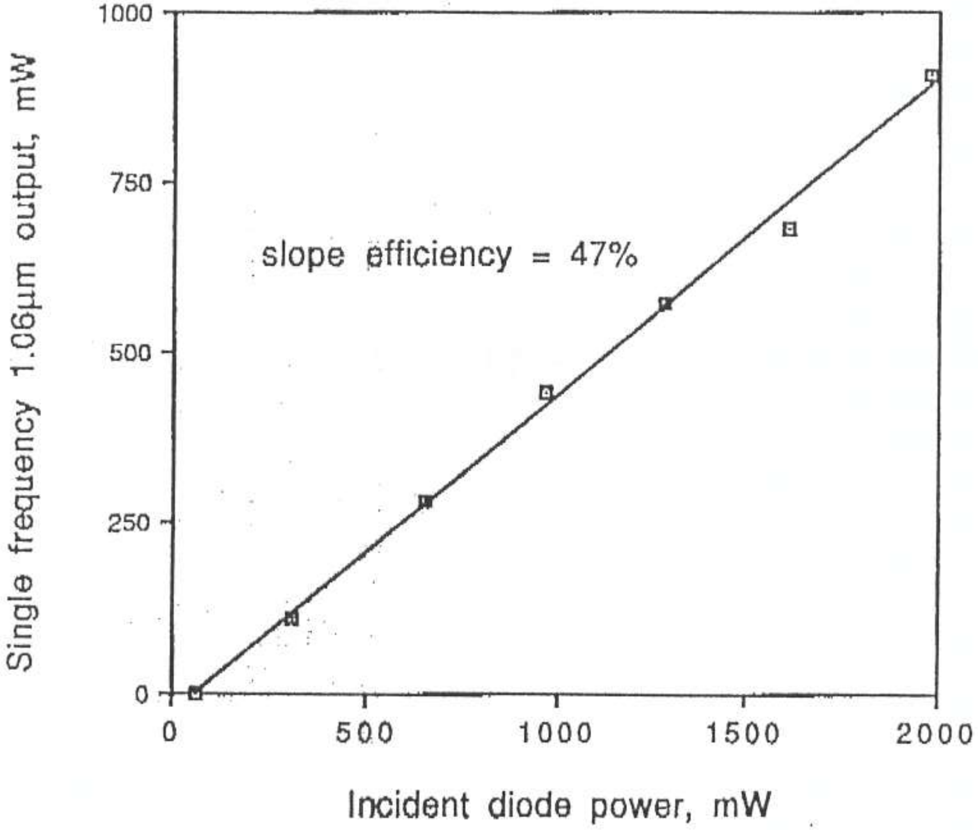


Conceptual space design (pump diodes not redundant)

Single side pumped - Linear resonator - two stage amplifier Configuration


master oscillator
diode pump
focussing optics
mode matching lens
slave oscillator
diode pump
photodiode
high reflector at 45° at 1.06 µm
anti-reflector at 45° at 0.8 µm


slope efficiency = 60.5%
Single frequency 1.06 μm output, mW
Incident diode power, mW
0
100
200
300
400
0
200
400
600


slope efficiency = 47%
Single frequency 1.06µm output, mW
1000
750
500
250
0
0
500
1000
1500
2000
Incident diode power, mW

Ball

CONCLUDING REMARKS

3-4

Recent developments in high power optical source technology for space communications

Richard Craig

Spectra Diode Labs., Inc.

IWOSC '90

December 6 and 7, 1990, ATR, Kyoto

Recent Developments in High Power Optical Source Technology for Space Communications

Richard Craig

Spectra Diode Laboratories
80 Rose Orchard Way
San Jose, Ca (408) 943-9411

Recently developed high power semiconductor lasers with long lifetimes are an enabling technology for space based communication links. This paper will review work at Spectra Diode Laboratories in both single mode lasers and partially coherent laser arrays that have application in space based systems.

The specific optical power and beam quality requirements on a laser diode for a space based communication link depend on the systems requirement, for example telescope size, link distance and data rate. Even without a specific link in mind we can break the laser sources down into two broad classes, beacons which require only partially coherent sources and typically operate at modest data rates, and data links which require diffraction limited spatial beam quality and operate at high data rates.

PARTIALLY COHERENT SOURCES

At SDL we have been commercially manufacturing high power partially coherent diode laser arrays since 1984. We have qualified a six element array for space in a hermetically sealed fiber optic package. This device delivered modest optical power (18mW) into the optical fiber (70 microns) and required extremely long operational life. We have to date collected in excess of 20,000 hours operating life data on a population of these lasers without a failure. Projected life for this population is well in excess of 200,000 hours.

Today we commercially sell packages that contain laser arrays that deliver 250 mW and 500 mW into 50 micron and 100 micron fibers respectively. We have projected lifetimes of these lasers in excess of 60,000 hours at room temperature operation. Even higher brightness appears possible with our newer laser designs in which we have demonstrated in excess of 2.0 Watts from a 50 micron, 0.4 NA fiber.

COHERENT SOURCES

The SDL-5410 is a 100 mW CW single mode real refractive index guided laser. The device has excellent beam quality, low relative intensity noise, and a narrow spectral linewidth. We have demonstrated mean time to failure at elevated temperature in excess of 20,000 hours. Projected lifetimes at room temperatures are in excess of 60,000 hours from unscreened units. Recently we have introduced the SDL-5420 which has a rated optical power of 150mW CW. The spatial beam is still diffraction limited at this power. Preliminary lifetest data suggests extremely long life operation.

One technique to obtain significantly higher optical power than is available with our single mode lasers is to use an external optical cavity to phase lock a laser array. Another promising area of work aimed at higher power coherent sources is to use a low power diffraction limited laser to feed a series of power amplifiers. At SDL we have been successful in obtaining in excess of 1 Watt of coherent power from a monolithic string of nine surface emitting amplifiers being fed by a single master oscillator.

Richard R. Craig received his B. S. Degree in physics from the University of California at Berkeley and Ph.d. in electrical engineering from UCLA in 1978 and 1985 respectively. In his thesis he demonstrated the first etched mirror unstable resonator semiconductor laser. In 1985 he joined the technical staff at Hughes Research Laboratories working primarily on the coherent additional of discrete lasers with optical phase conjugation. In 1989 he joined Spectra Diode Laboratories as a senior member of the technical staff responsible for new product development.

Recent Developments of High Power Optical Source Technologies for Space Communications

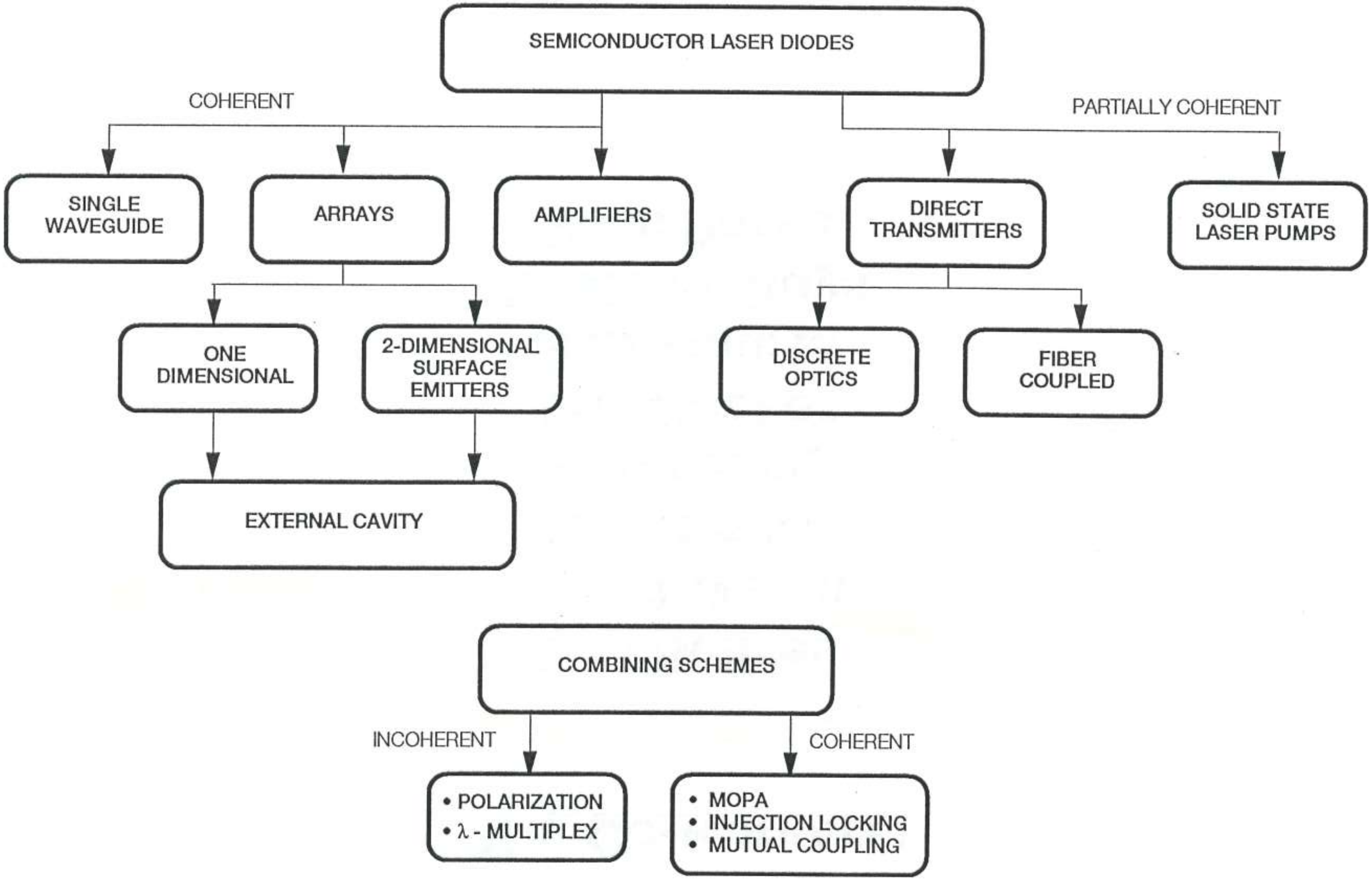
Richard Craig

SPECTRA DIODE LABORATORIES

SDL Co-workers:

Don Scifres
David Welch
John Endriz
Hsing Kung
Erik Zucker
Rob Waarts
David Mehuys
Ross Parke

Transmitter Options



SEMICONDUCTOR LASER DIODES

COHERENT

SINGLE WAVEGUIDE

ARRAYS

AMPLIFIERS

ONE DIMENSIONAL

2-DIMENSIONAL SURFACE EMITTERS

EXTERNAL CAVITY

PARTIALLY COHERENT

DIRECT TRANSMITTERS

DISCRETE OPTICS

FIBER COUPLED

SOLID STATE LASER PUMPS

COMBINING SCHEMES

INCOHERENT

- POLARIZATION
- λ - MULTIPLEX

COHERENT

- MOPA
- INJECTION LOCKING
- MUTUAL COUPLING

DS120889

Partially Incoherent Transmitters

- Previous Space Qualified Work at SDL
  - Highly Reliable Fiber Coupled Array
  - 5 W Beacon
- Present Commercial Options
- Future Prospects
  - Higher Brightness

Three Watt Link

Source

- $P = 3$ Watts
- Source Diameter = 0.3 mm, 0.3 N.A.

Transmitter

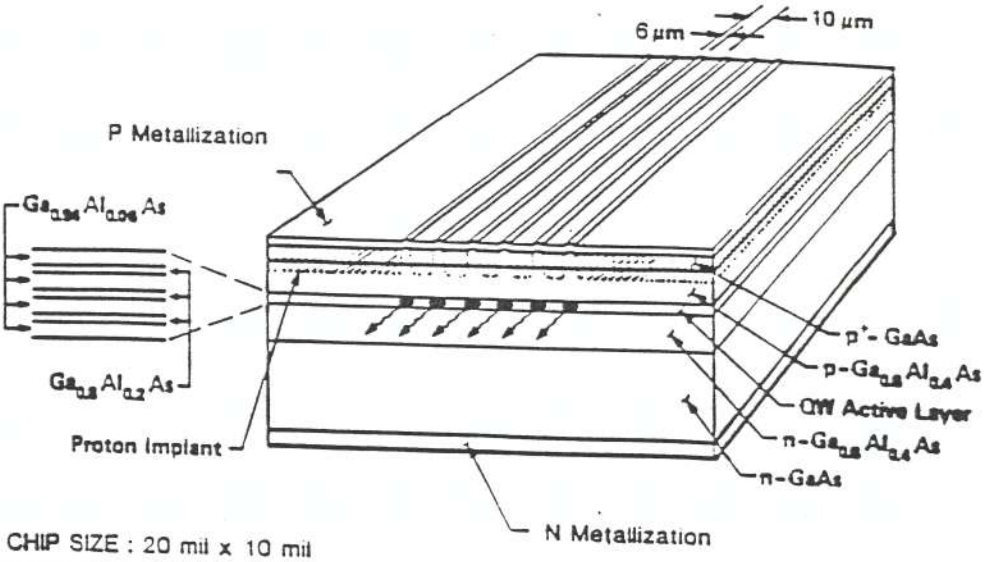
- 25 cm Diameter, 40 cm Focal Length, 0.3 N.A., Transmission Optics Produces 0.72 mRad Divergence

Receiver

- At 125 photons/bit, 25 cm Diameter Receiver:

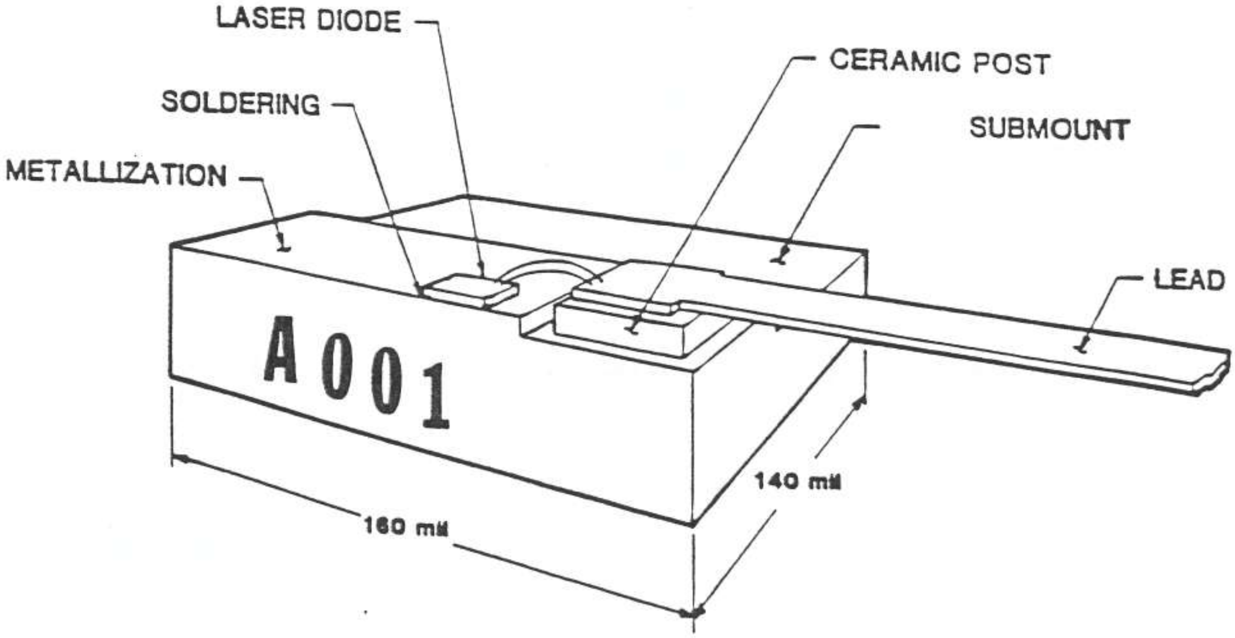
Data Rate	Range
10^8 Bits/sec.	11,000 km
10^7 Bits/sec.	35,000 km

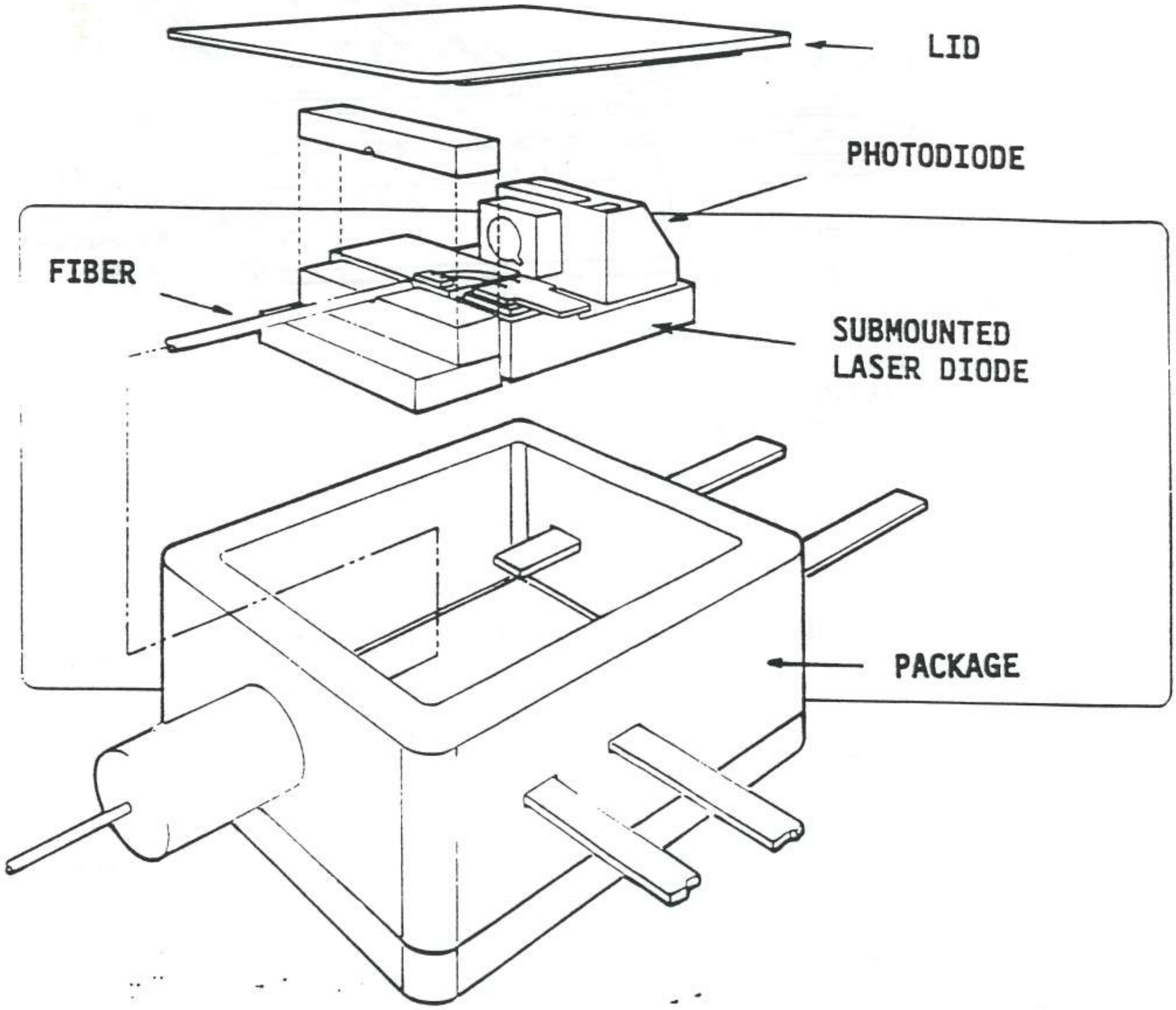
6 STRIPE LASER ARRAY DESIGN



CHIP SIZE : 20 mil x 10 mil
CAVITY LENGTH : 10 mil
THICKNESS ~ 3.5 mil

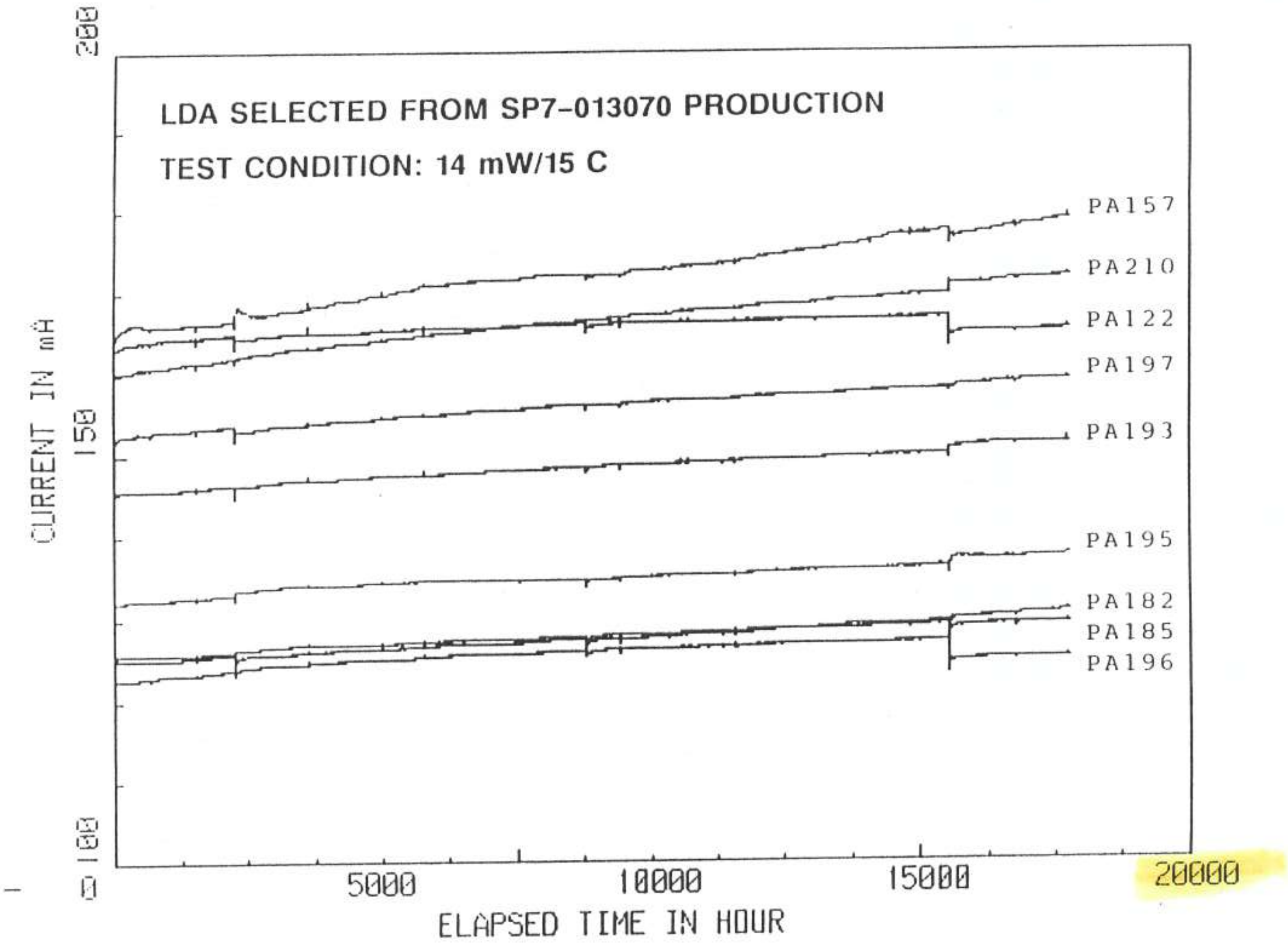
SUBMOUNT LASER DIODE DESIGN (79SP12-10 PARTS)



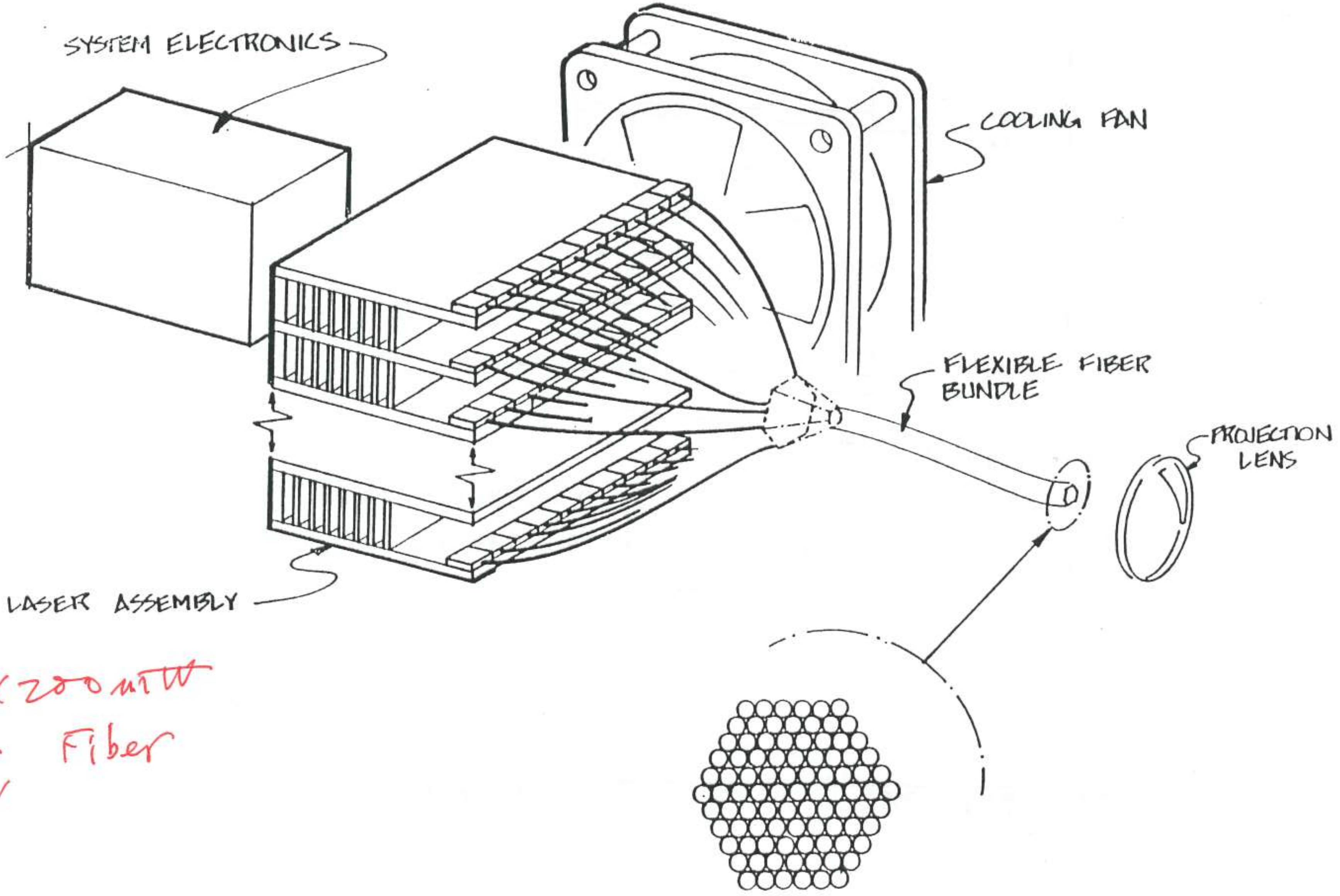


THE LASER DIODE ASSEMBLY (LDA)

LDA LIFE TEST DATA

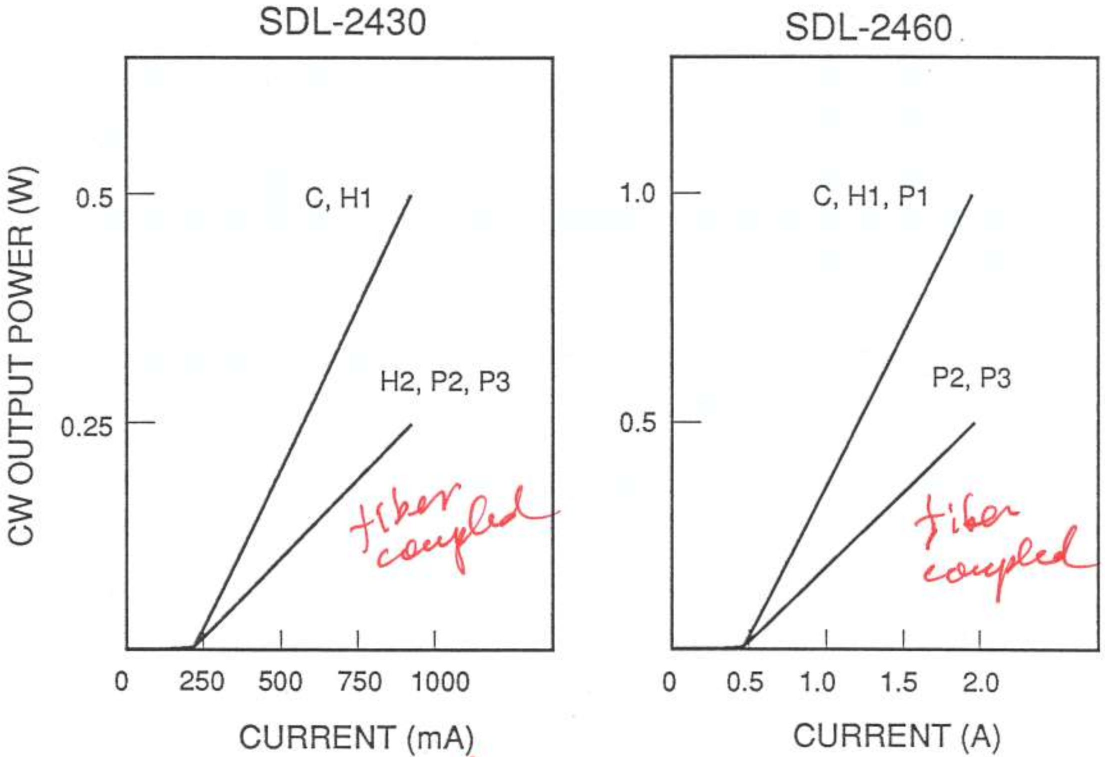


5 W Average Power Satellite Pointing and Tracking Beacon



25X200mW
=5W, Fiber

SDL-2400 Optical Characteristics

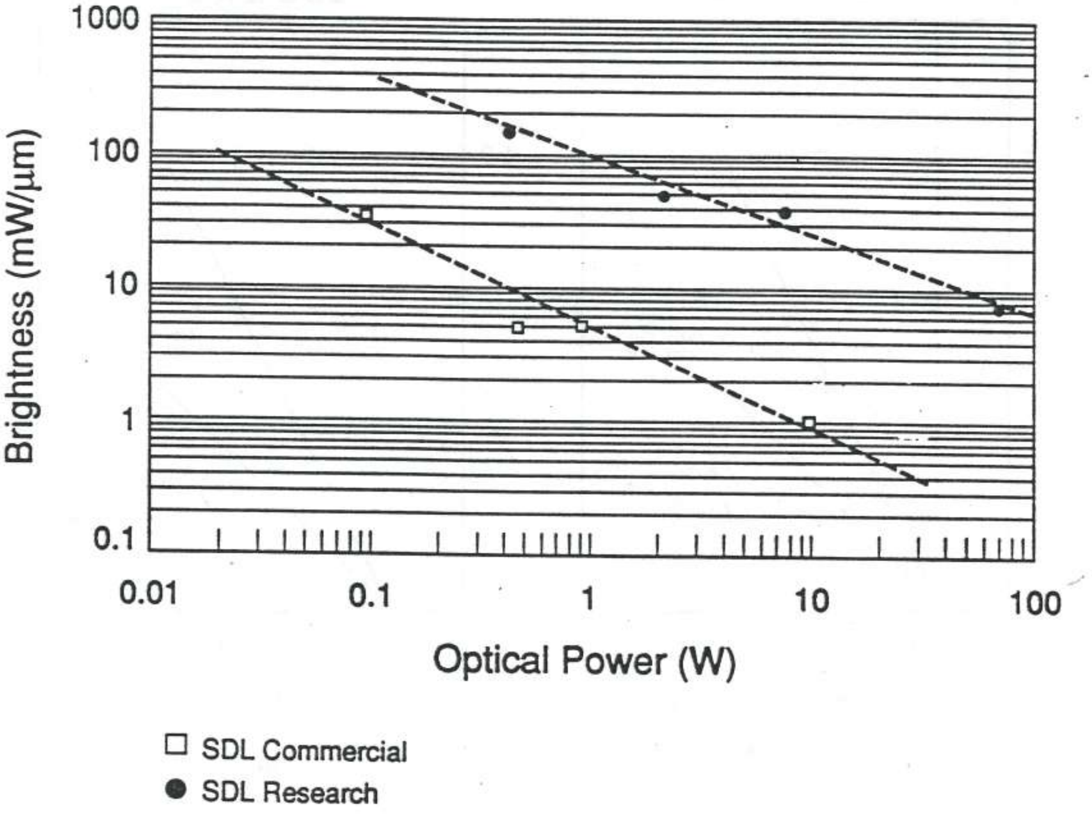


100μm Aperture diode

200μm

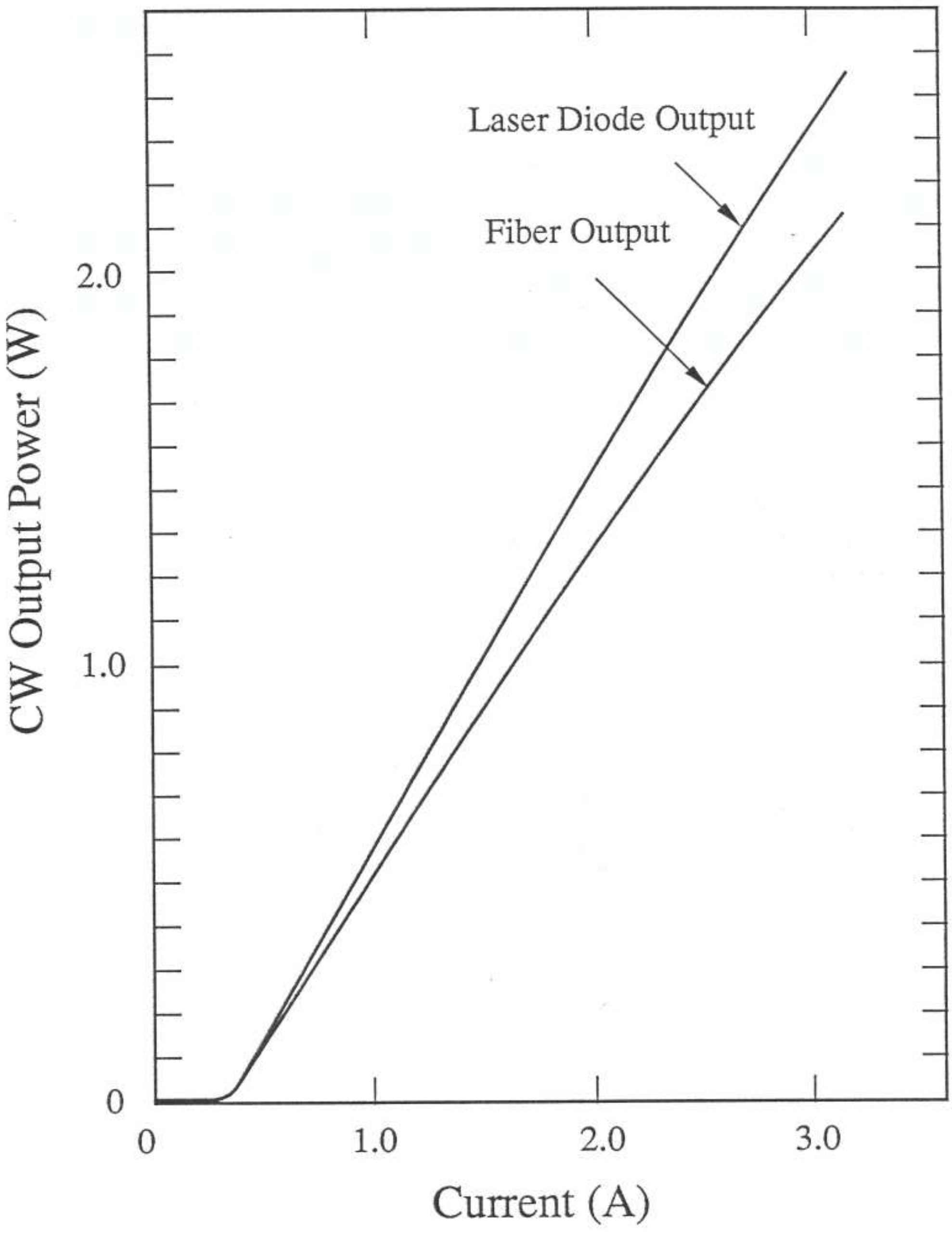
Power vs. Brightness for SDL Lasers

(CW Operation)



Fiber Coupled Array

50 μm Diameter, 0.4 NA



- 100 μm Aperture
- Low divergence ~~angle~~ Laser
- 100ths to ....

Coherent Transmitters

- **SDL 5410**
- **SDL 5420** higher Power Version
- **Future Prospects**

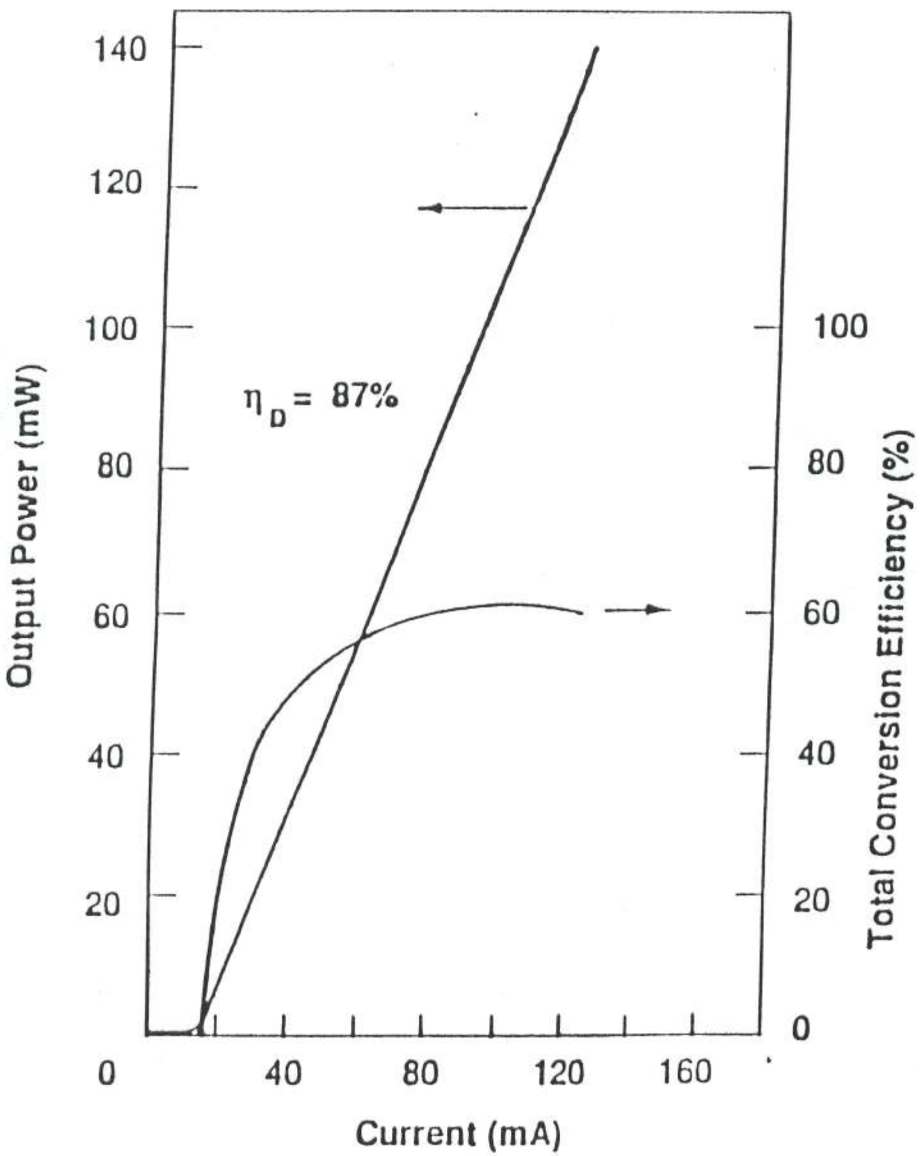
Approximate Geo-Geo Laser Comm Link Power Requirements

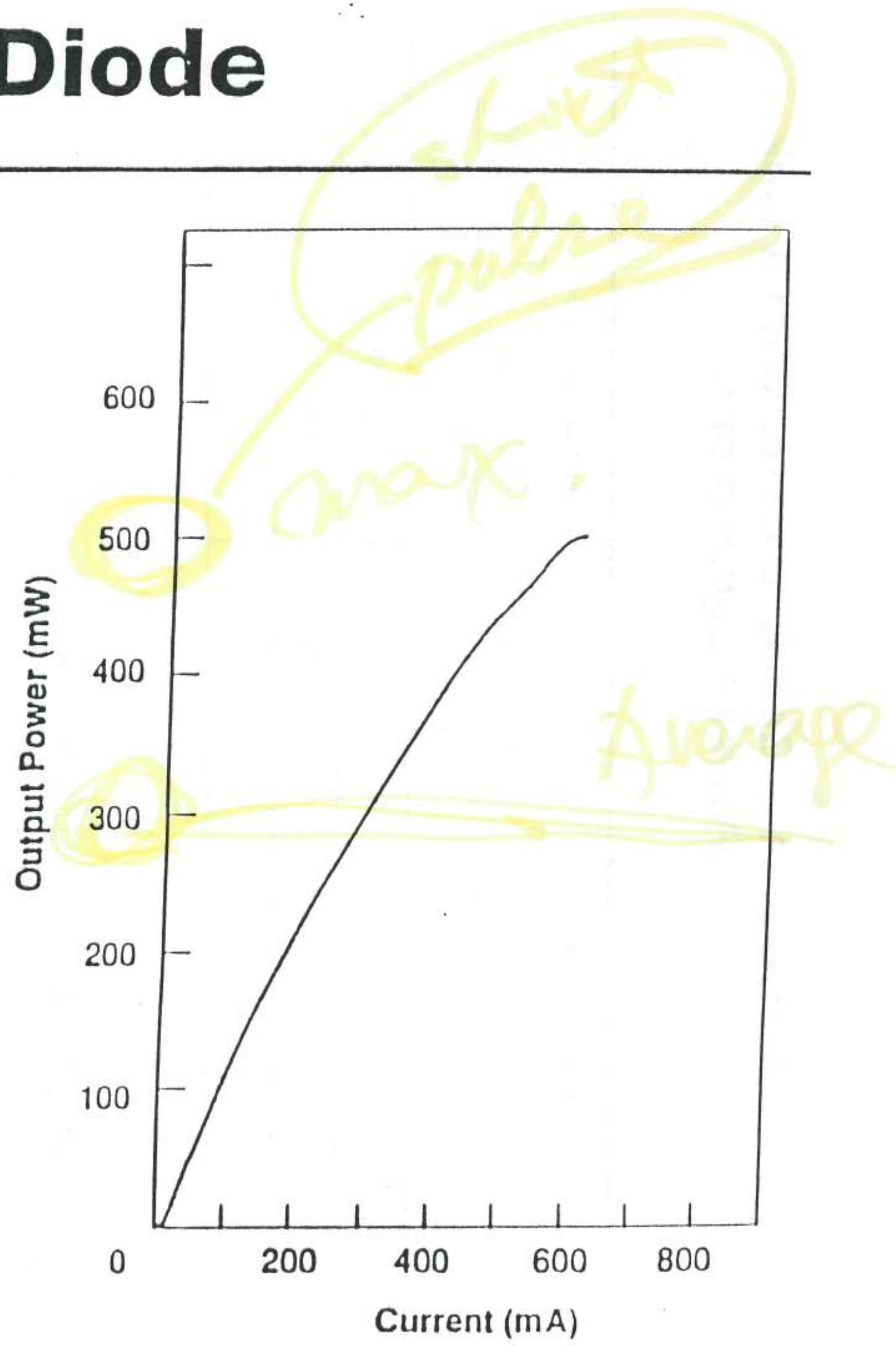
Telescope Dia	**Peak Laser Power**		
	1 Mb/sec	10 Mb/sec	100 Mb/sec
10 inch	15 mW	150 mW	1.5 W
8 inch	23 mW	230 mW	2.3 W
5 inch	60 mW	600 mW	6 W
3 inch	167 mW	1.67 W	16.7 W

Assumptions:

- 85,000 km link
- 10^{-6} BER
- 1 mrad receiver field of view
- 3dB system margin
- moon background
- 15 Å filter
- Manchester modulation
- APD

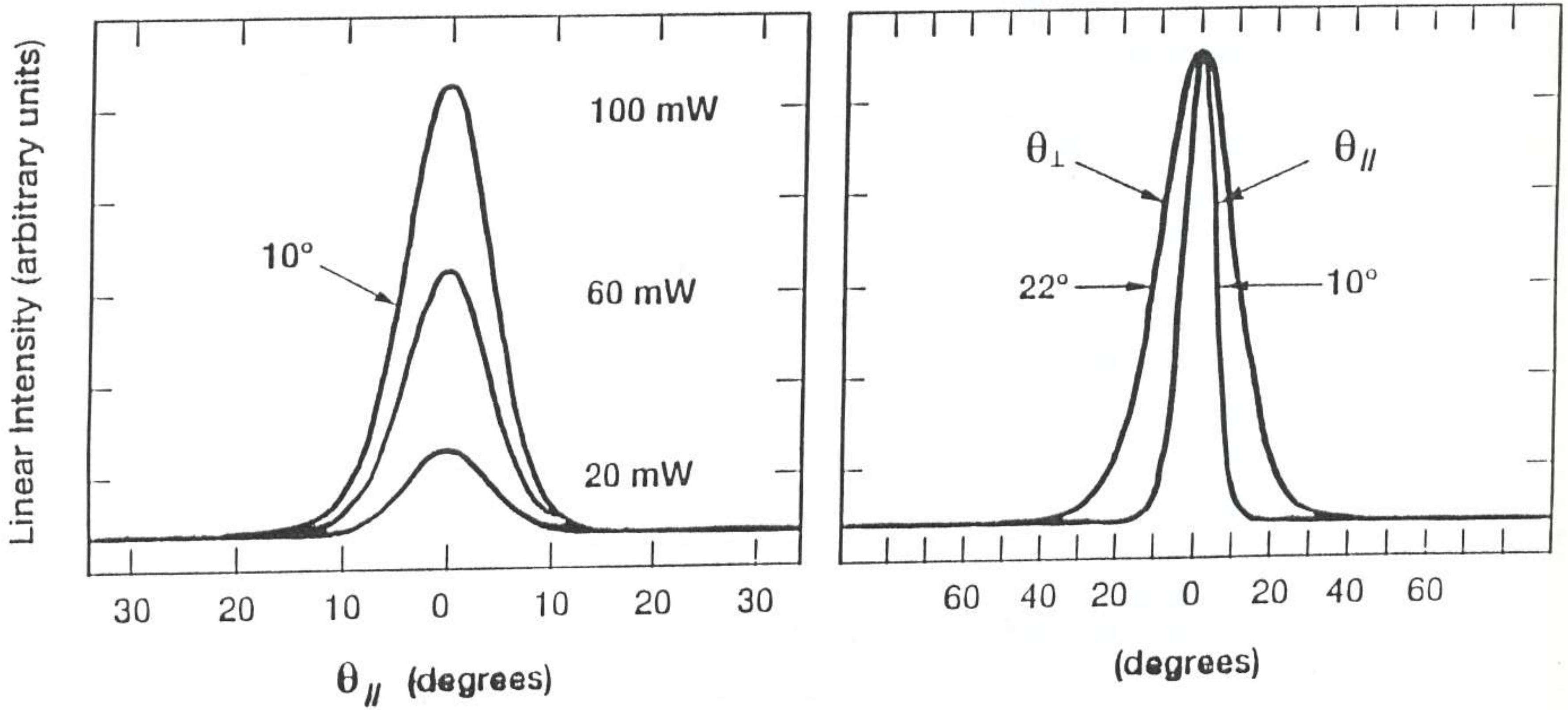
Single Stripe Laser Diode





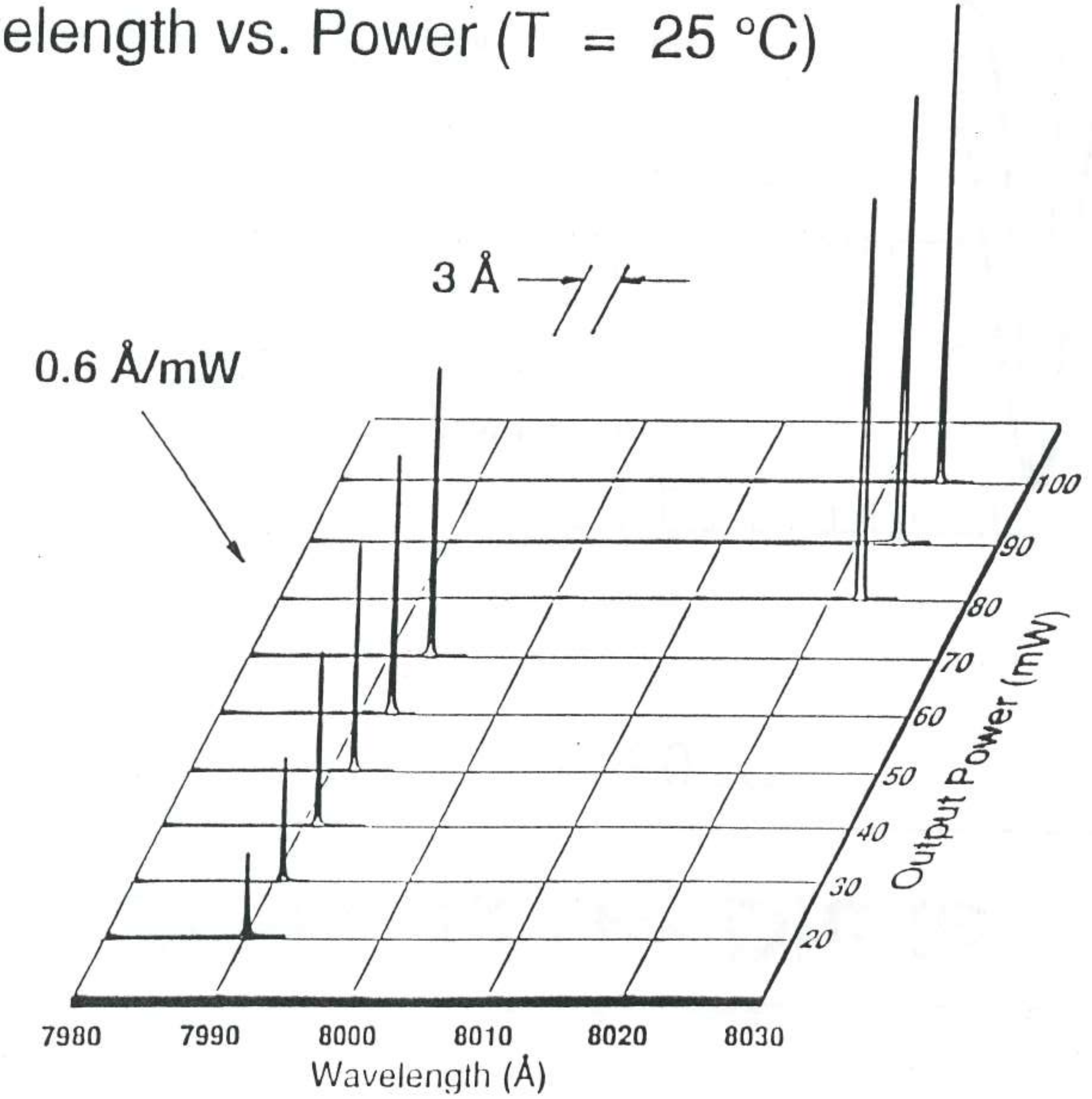
Single Stripe Laser Diode

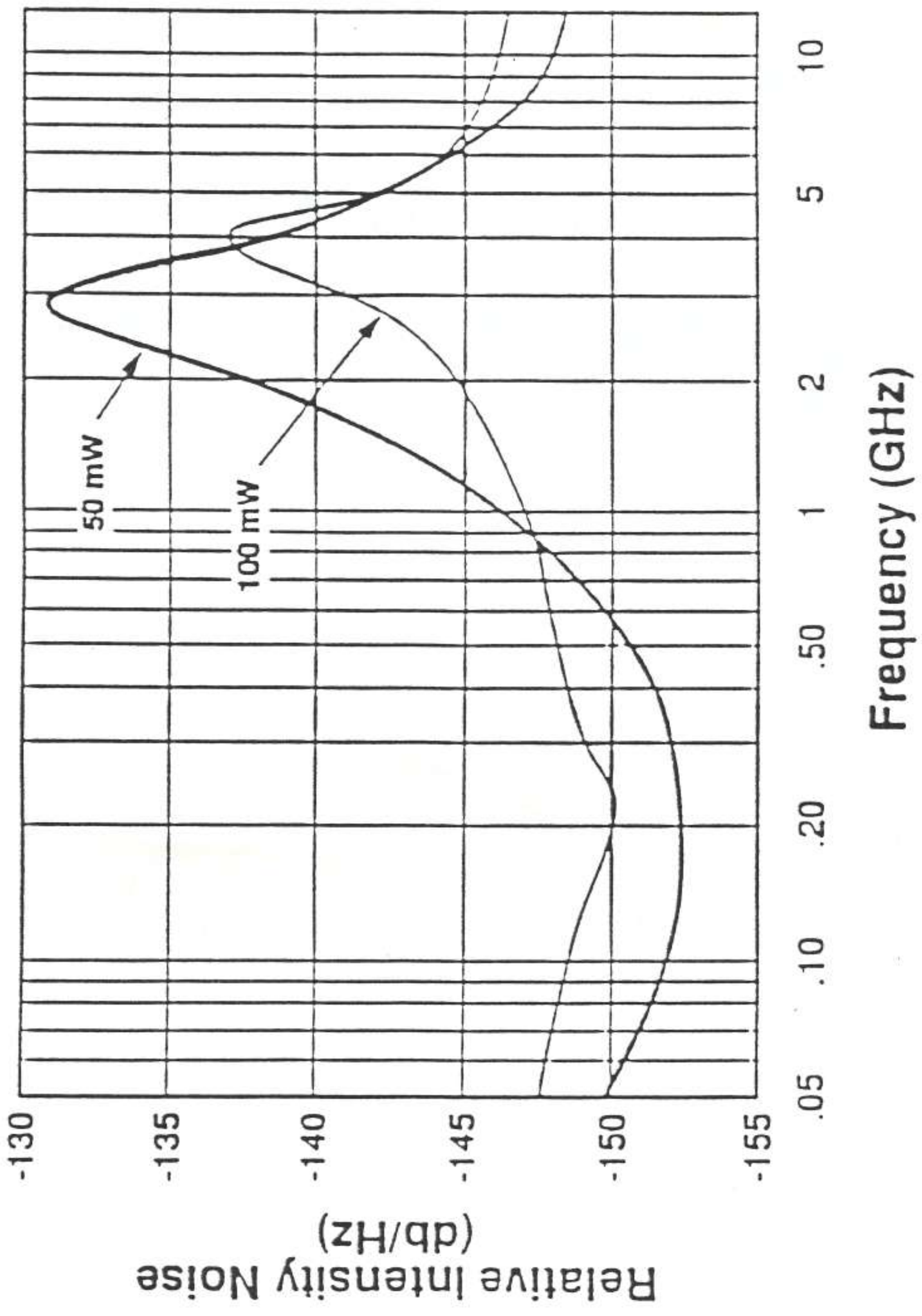
After 1000 hours, 100 mW, at 50 °C



Single Stripe Laser Diode

Wavelength vs. Power (T = 25 °C)




Relative Intensity Noise
(db/Hz)
-130
-135
-140
-145
-150
-155
.05
.10
.20
.50
1
2
5
10
Frequency (GHz)
50 mW
100 mW

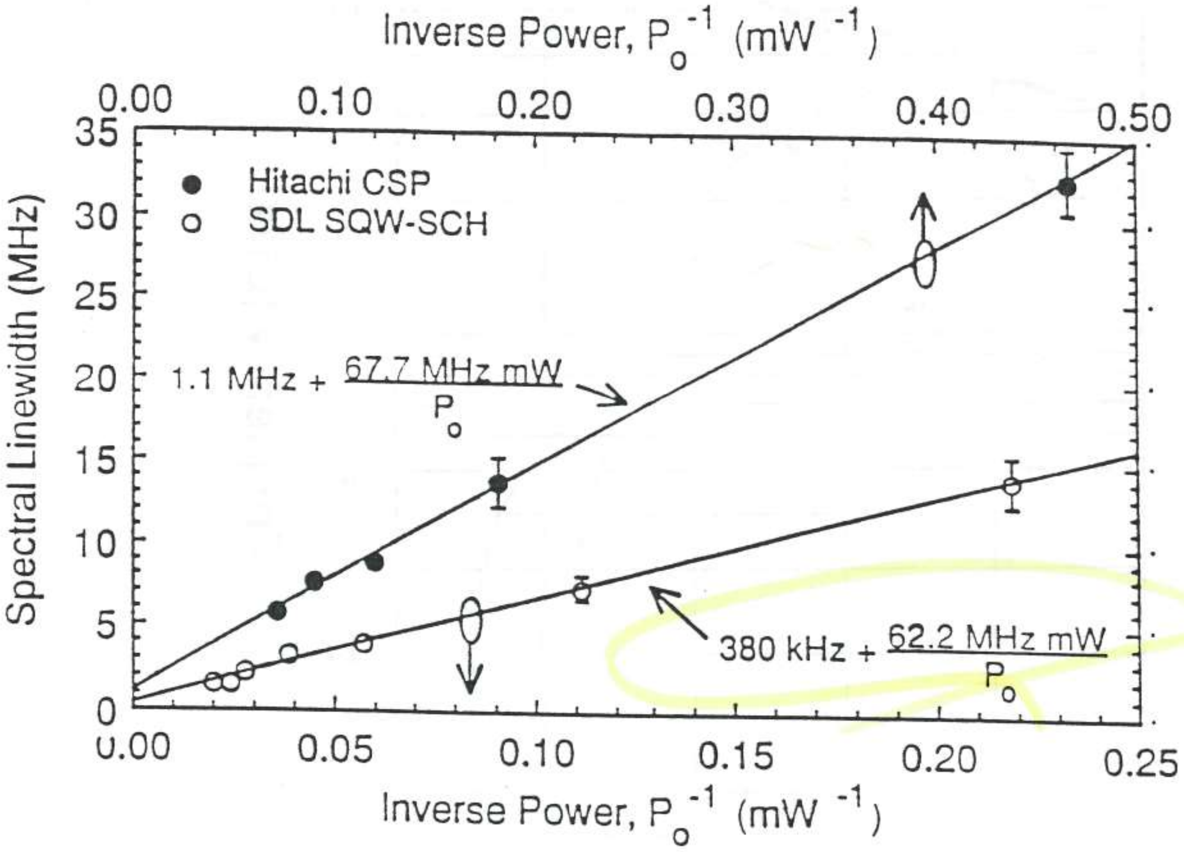
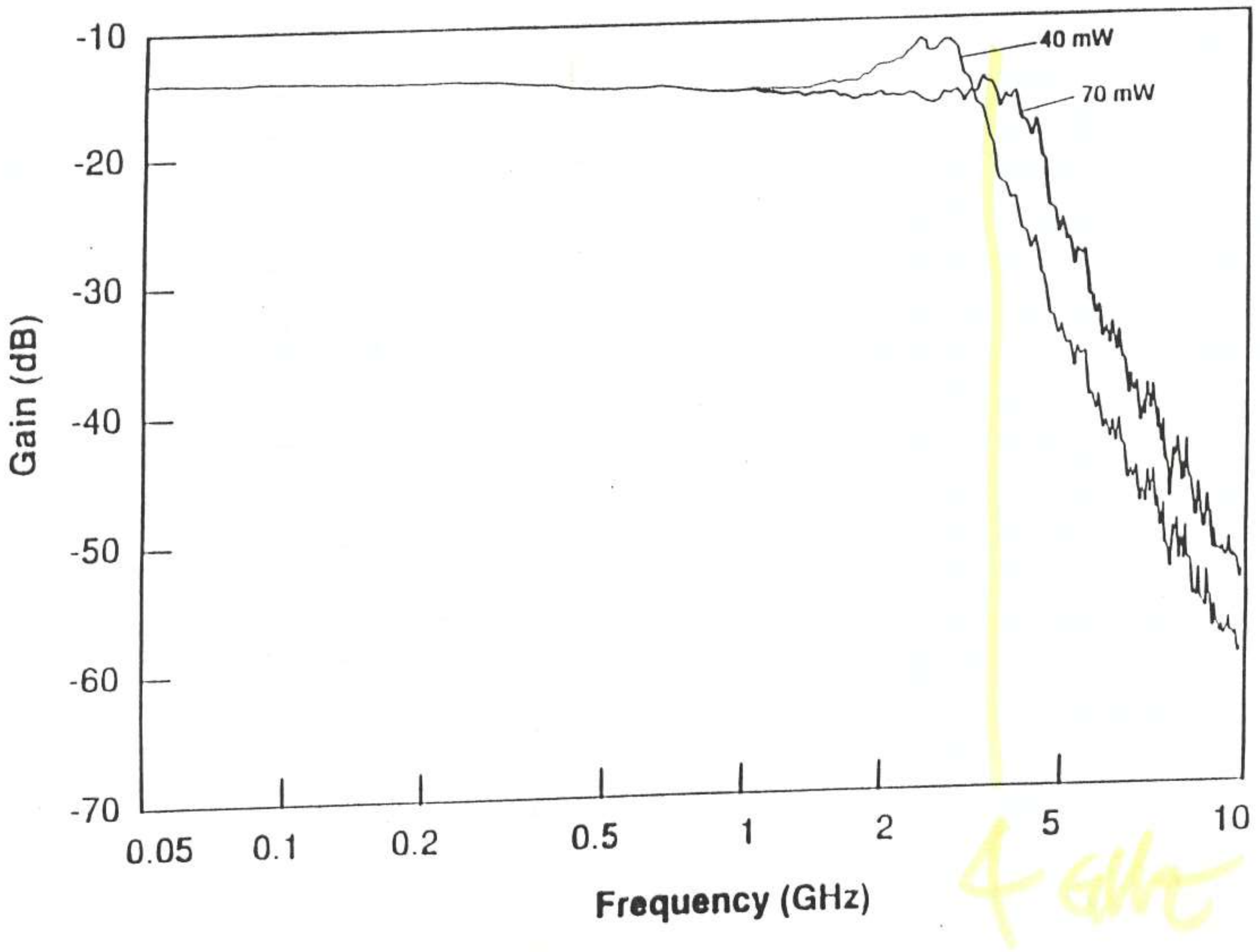
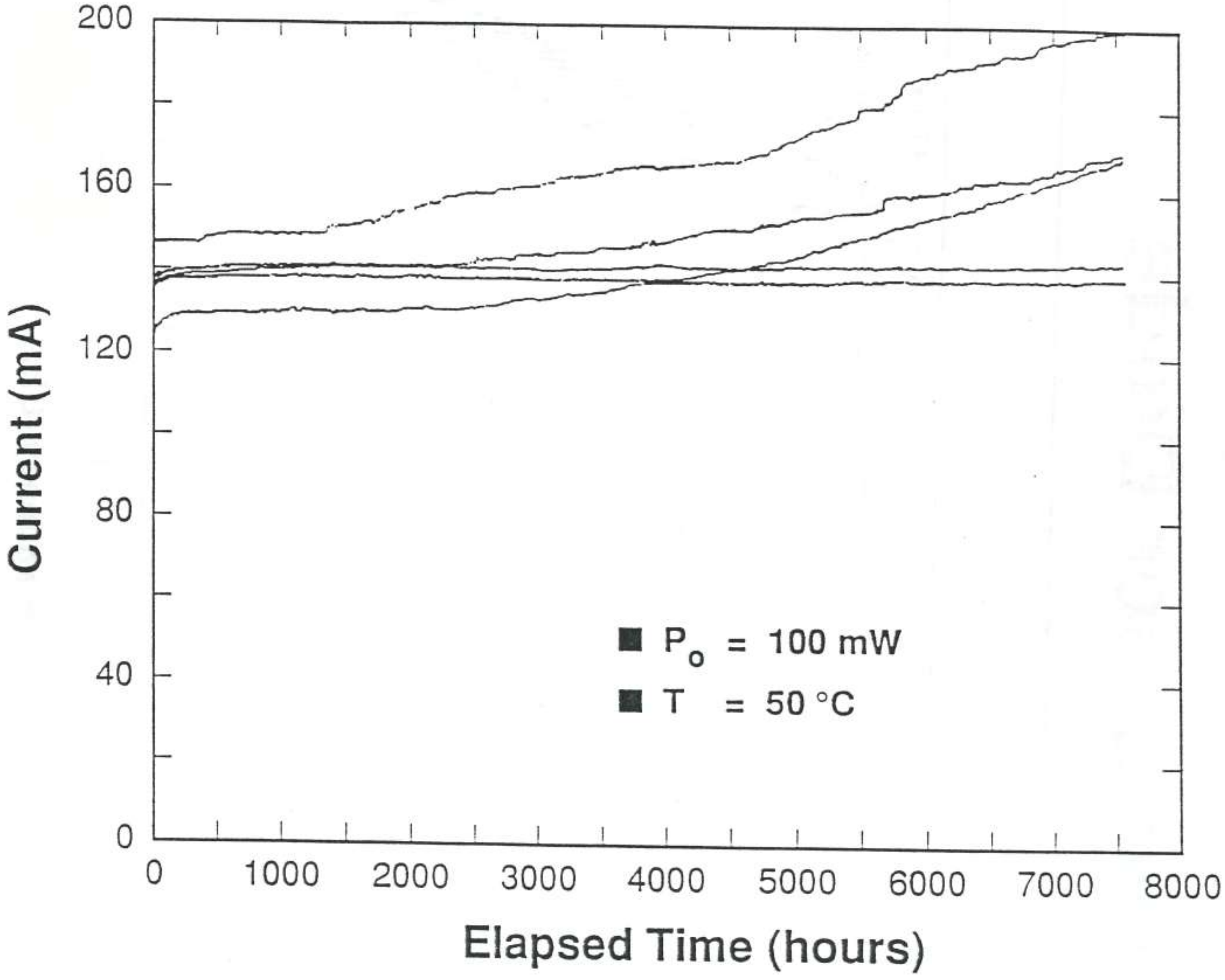

Inverse Power, P_o^{-1} (mW $^{-1}$)
0.00
0.10
0.20
0.30
0.40
0.50
35
30
25
20
15
10
5
0
Spectral Linewidth (MHz)
● Hitachi CSP
○ SDL SQW-SCH
1.1 MHz + $\frac{67.7 \text{ MHz mW}}{P_o}$
380 kHz + $\frac{62.2 \text{ MHz mW}}{P_o}$
0.00
0.05
0.10
0.15
0.20
0.25
Inverse Power, P_o^{-1} (mW $^{-1}$)

Figure 3

Single Stripe Laser Diode



SDL-5410
Constant Power Lifetest



Average Lifetime = 20,000 hrs at 50 °C

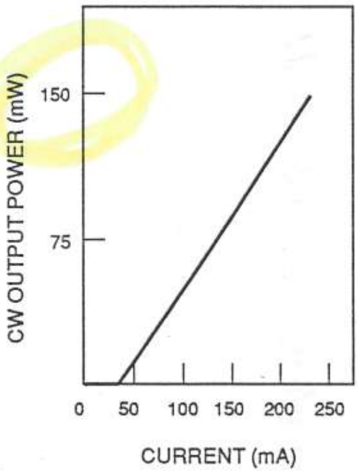
Extrapolated Lifetime (E_a = 0.5 - 0.7 eV) $\geq$ 60,000 hrs at 25 °C

Summary Of Characteristics

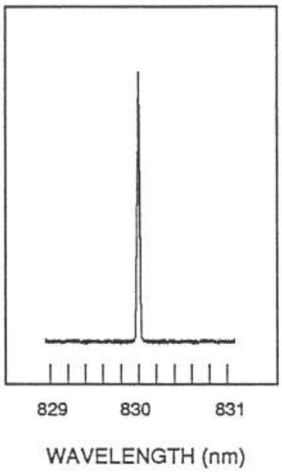
- P_{MAX} - 500 mW
- I_{th} ~ 20 mA
- η_D ~ 70 - 80%
- η_T ~ 60%
- 1.5 MHz Linewidth
- Single Longitudinal/Transverse Mode To 180 mW
- > 4 GHz Bandwidth
- < $\lambda/20$ RMS Phase Error
- < 2.5 : 1 Aspect Ratio
- 8 Å Continuous Tuning With Temperature
- Reliable Emission At 100 mW Diffraction Limited Output

SDL-5420 Optical Characteristics

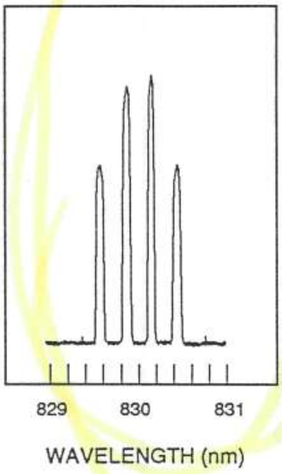
LIGHT vs. CURRENT CHARACTERISTICS



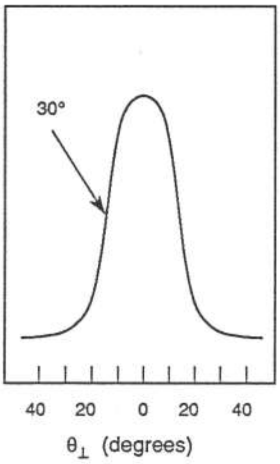
TYPICAL EMISSION SPECTRUM TO 100 mW



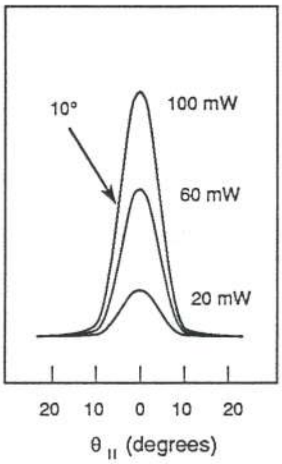
TYPICAL EMISSION SPECTRUM OVER 100 mW



FARFIELD ENERGY DISTRIBUTION

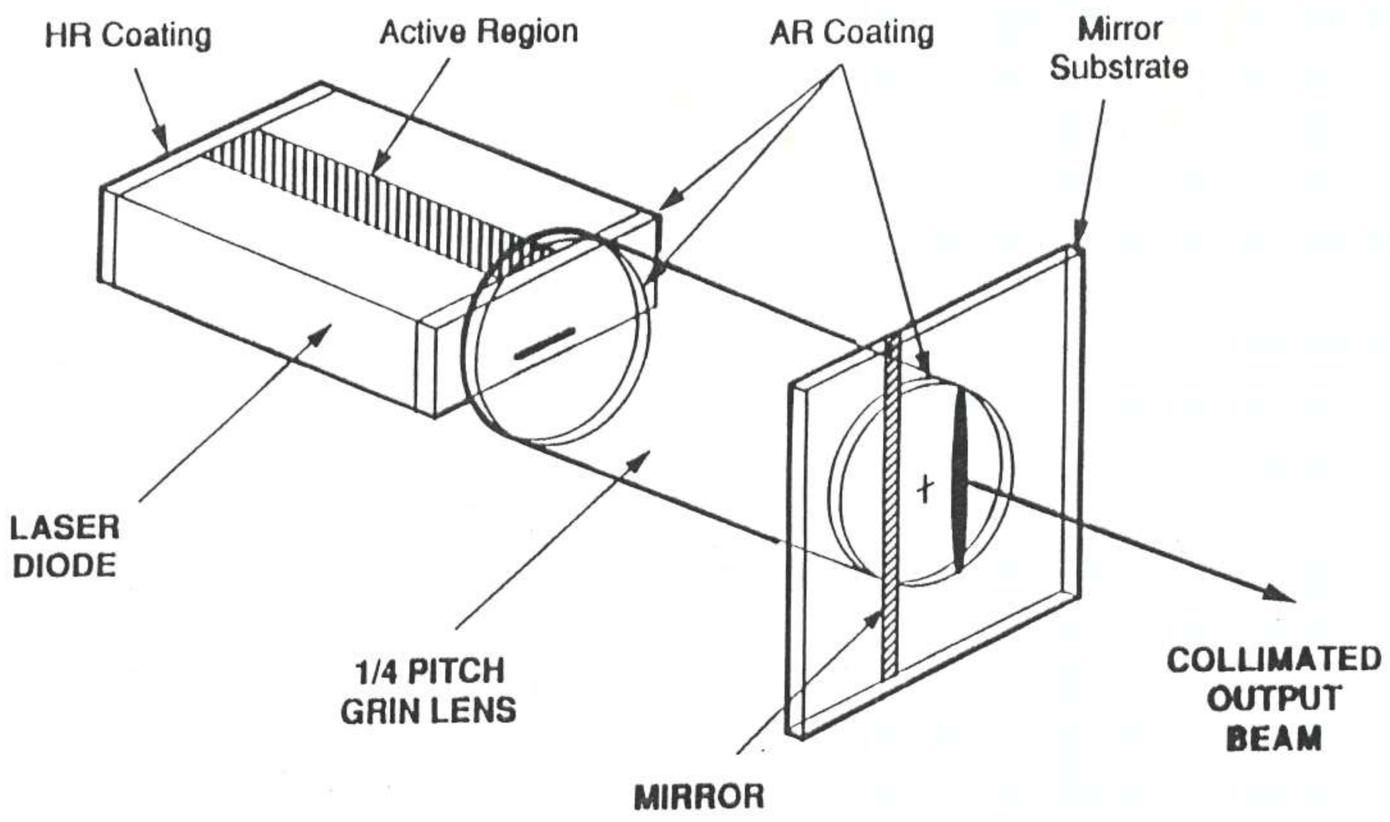


FARFIELD ENERGY DISTRIBUTION



GRIN Cavity Design

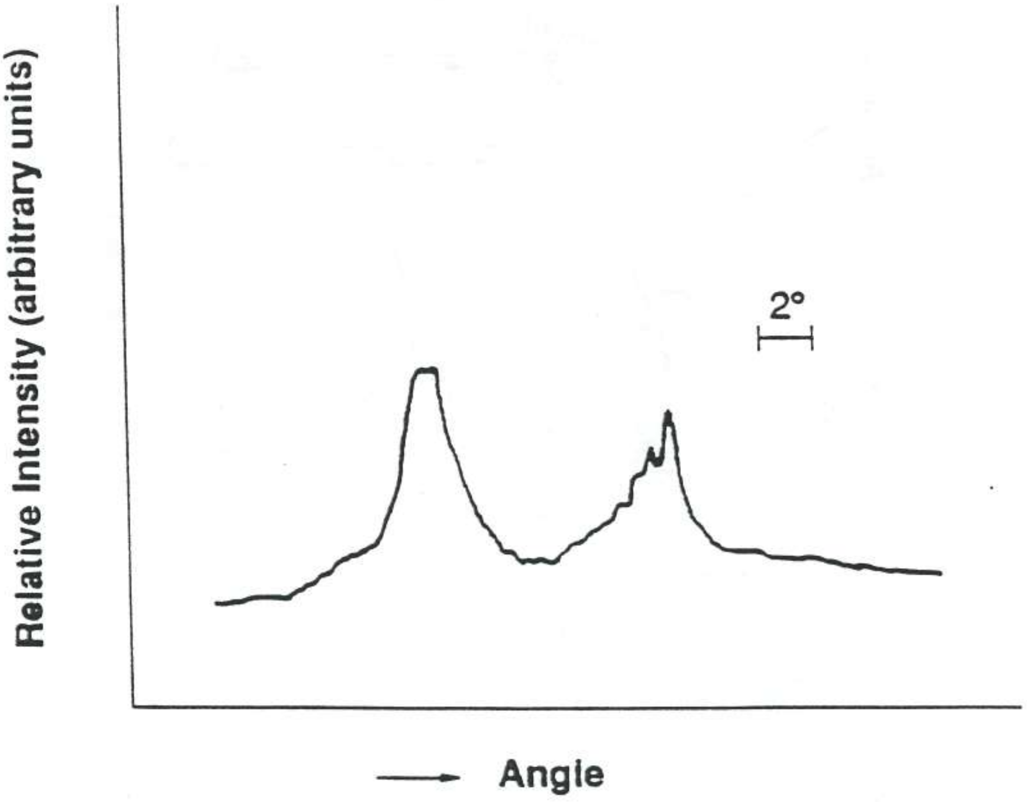
not
commercial



RW081200

Far Field
(cw, no feedback)

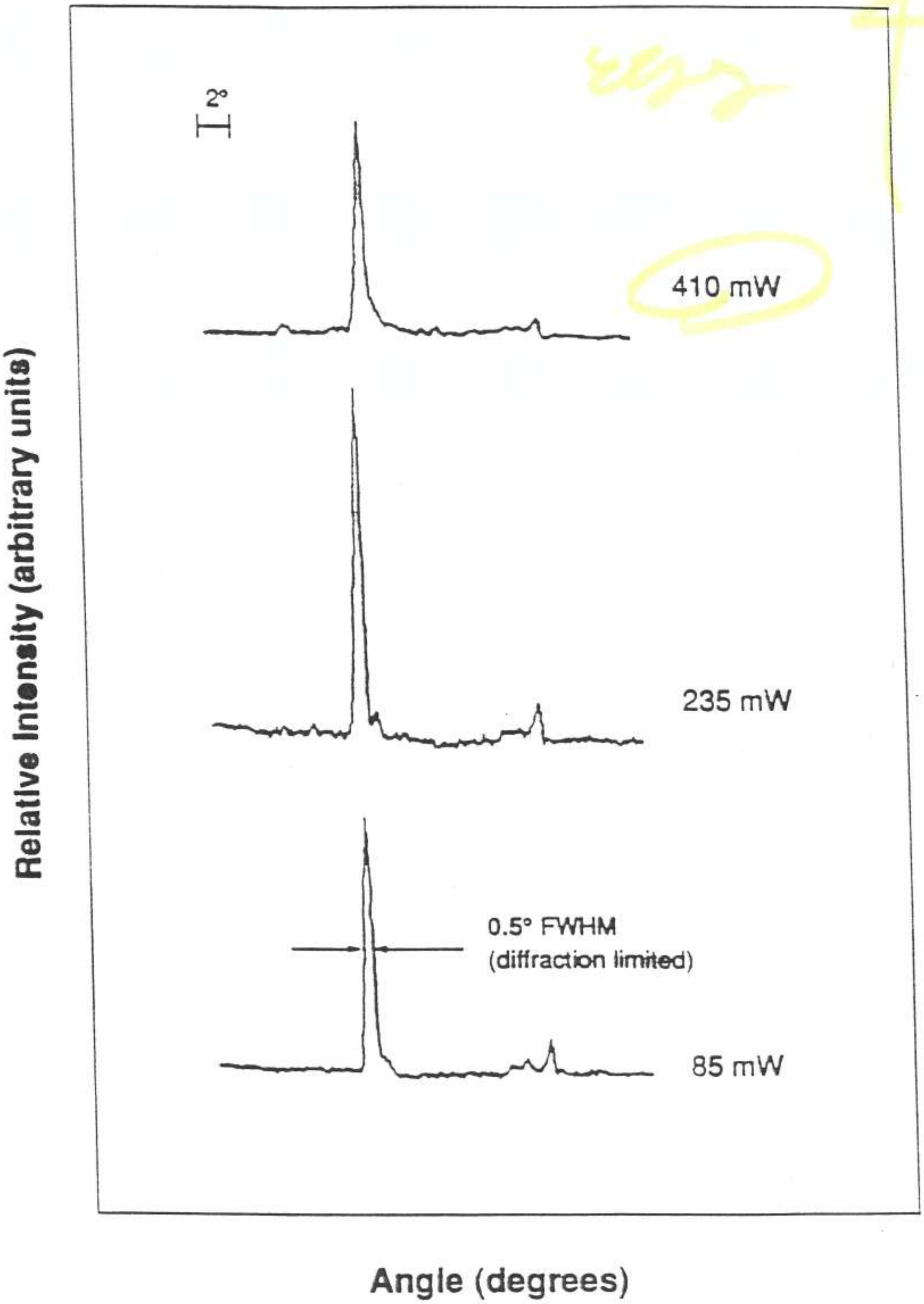
SDL-2420: 100 µm aperture
10 gain guides



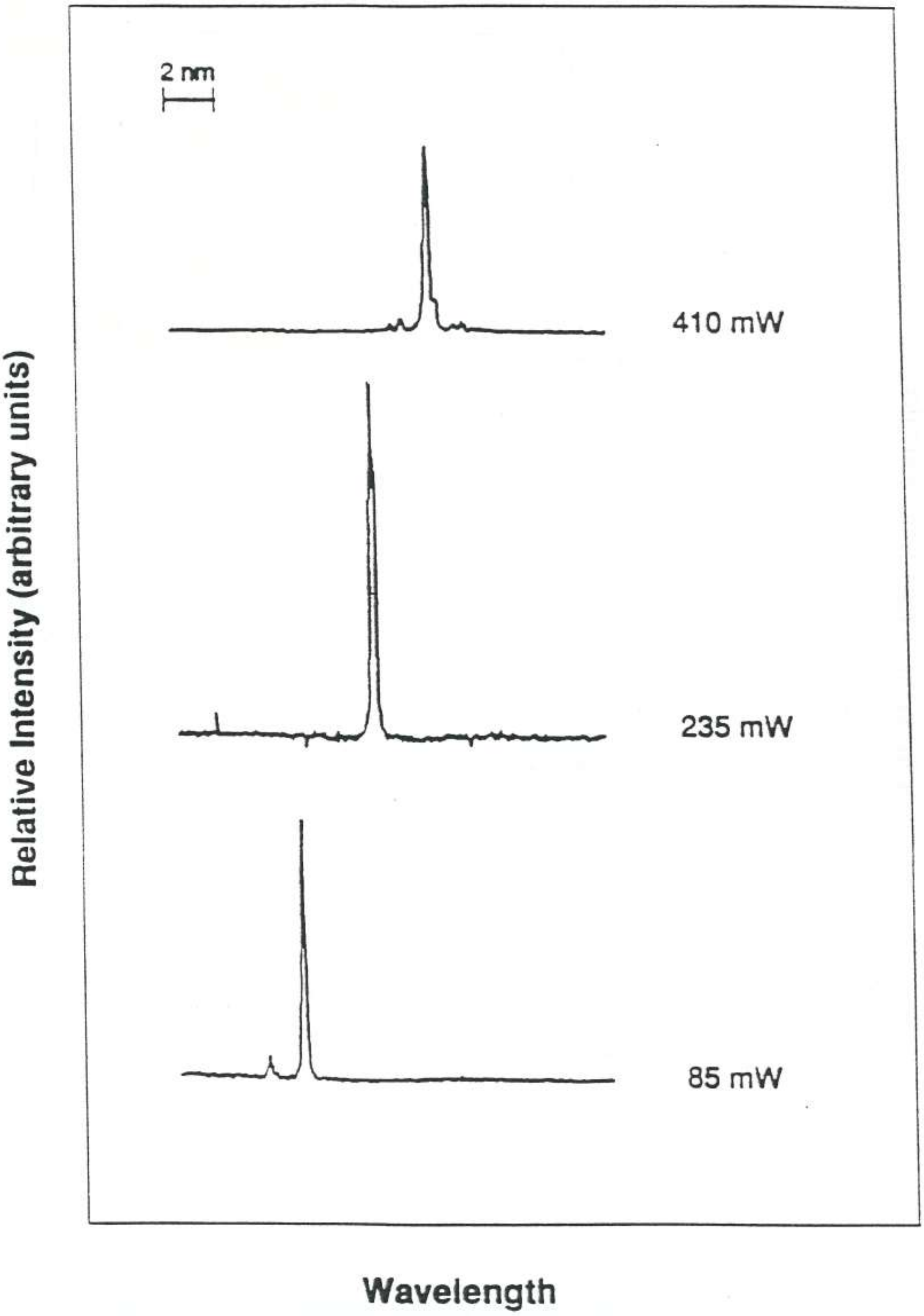
RW101189

Far Field
(CW)

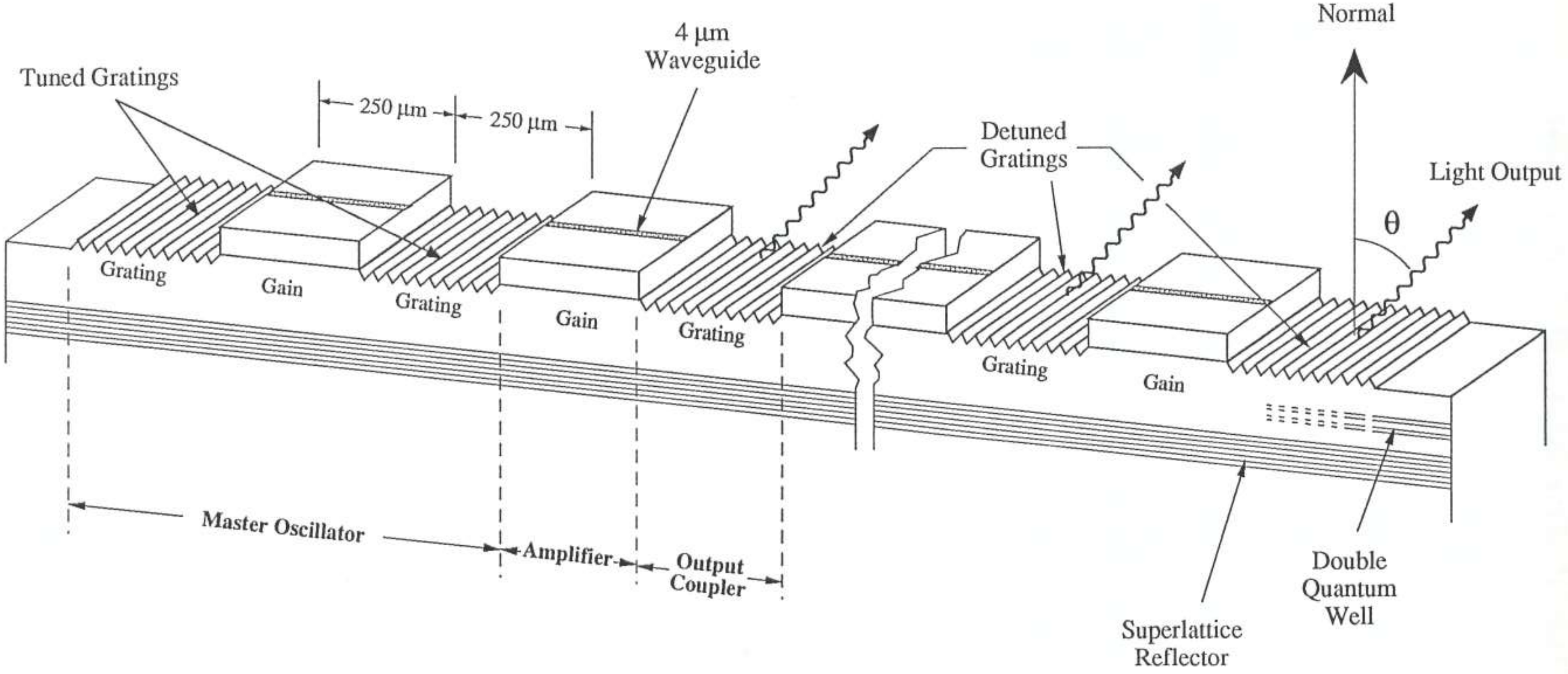
beam broad!



Spectrum
(CW)


2 nm
410 mW
235 mW
85 mW
Relative Intensity (arbitrary units)
Wavelength

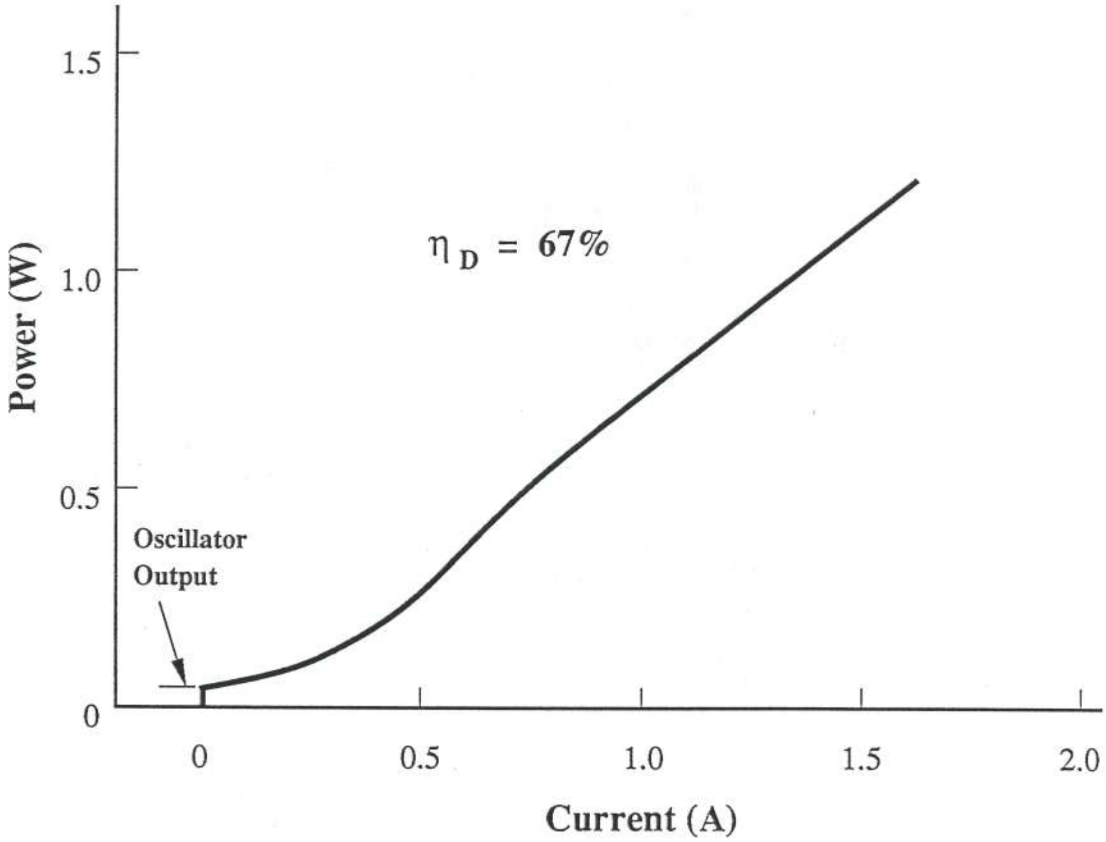
Monolithically Integrated Master Oscillator/Power Amplifier



Is that clear!

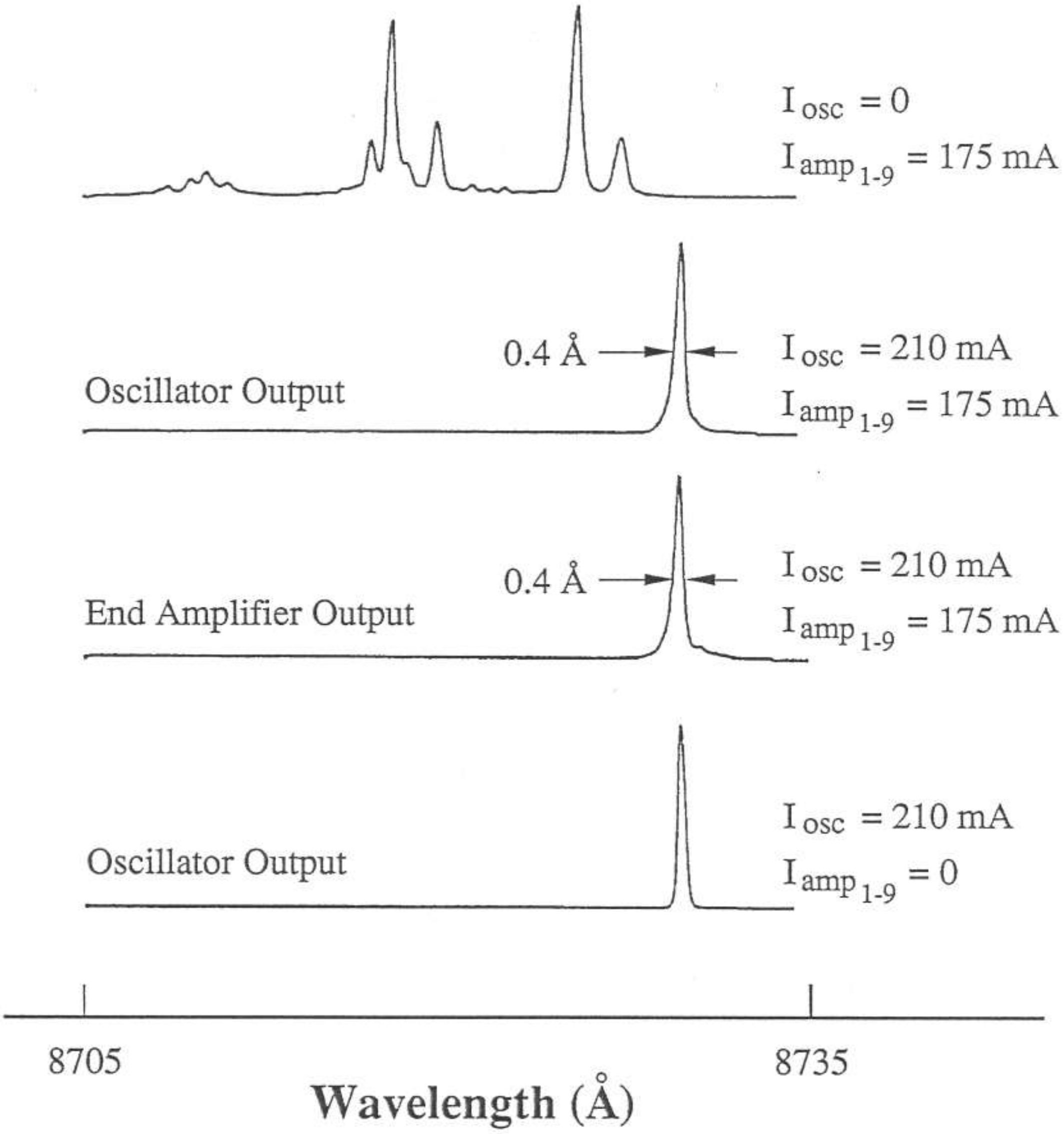
DM071990

M-MOPA
Oscillator plus 9 Amplifiers

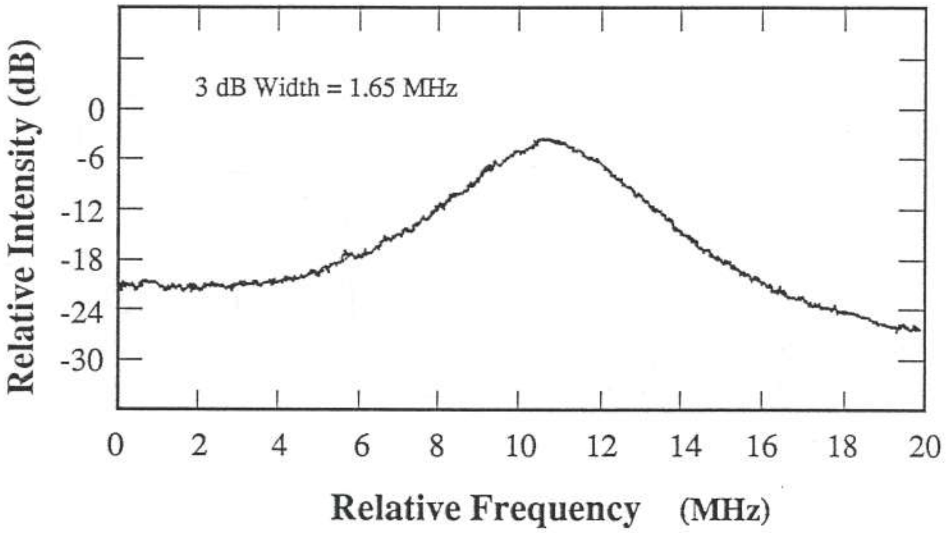


M-MOPA Spectrum

($P_{out} = 1$ W)



M-MOPA
Spectra Linewidth



Laser Solutions

coherent
clean (MIT) a 方法

	Demonstrated (cw)	Projected (cw)
• Single Mode Diode Lasers With Polarization Combiner	200 mW	300 mW
• Single Mode Diode Lasers with Wavelength Combiner (6)	150 mW	600 mW
• External (GRIN) Cavity Laser	400 mW	> 1 W
• MOPA	100 mW	> 1W
• Injection Locked	500 mW	> 1 W
• Y-Guide	150 mW	> 1 W
• 2-D Arrays	—	> 10 W
• Diode Pumped Solid State	3 W	> 10 W
• Fiber Coupled Diode Lasers (Space-Qualified)	28 mW/5 W	—

1 W : still pulse

これから、2〜3年中に
商品 見込みがあるか.

Session 4

Research on Optical Space Communications III

4-1

Free-space simulator for laser transmission

Masayuki Fujise

ATR Optical and Radio Comms. Res. Labs.

IWOSC '90

December 6 and 7, 1990, ATR, Kyoto

Free-Space Simulator for Laser Transmission

Masayuki Fujise

ATR Optical and Radio Communications Research Laboratories

Seika-cho, Soraku-gun, Kyoto 619-02, Japan
Telephone +81-7749-5-1511
Facsimile +81-7749-5-1508

Abstract

We propose the concept of a "free-space simulator for laser transmission" and show the development of a simulator to evaluate optical beam control subsystems for an optical intersatellite link (ISL).

Precision optical beam control technologies, such as (1)extremely low divergent beam shaping, (2)pointing/acquisition/tracking and (3)point ahead control, allow us to extract the potential advantages of an optical ISL system. However, it is difficult to evaluate their performances, because an optical ISL is operated under far-field optical beam condition. Most of developments has been made taking the near-field approach and has been evaluated analytically. Some open range approaches are under consideration in several research institutes.

Our approach is the compact range which can simulate the far-field conditions in a laboratory by utilizing a large aperture diffraction limited lens. This optical compact-range approach makes it possible to simulate the dynamic beam control environment in an optical ISL as well as implement static far-field conditions. In this presentation, we propose the concept of a "free-space simulator for laser transmission".

The simulator now under development has the capability to evaluate an optical antenna with a 200mm aperture diameter with accuracy on the μrad order. The diffraction limited plano-convex lens (260mm diameter and 17.5m focal length) made by NIKON has optical tolerance of λ/20 peak to peak on the plano side and λ/10 on the convex side. To capture the image of far-field pattern (FFP) formed on focal plane of the lens, we used a CCD camera with 13μm square pixels. The results of the FFP implementation test show that this simulator can estimate the far-field pattern with an accuracy on the μrad order.

We measured FFPs to evaluate optical transmitter performance. For reference, we measured a FFP formed by a mask that is matched the pattern of the telescope aperture. Then, (1)the optical antenna + He-Ne laser source, and (2) the optical antenna + LD source were measured. It is expected that the effective power actually transmitted by optical transmitter can be estimated by using this simulation technique.

The measurement was substantially affected by atmospheric turbulence and environmental vibration. We have just introduced a "scintillation-free chamber" to reduce the atmospheric effects and quite stable measurement conditions are obtained.

We plan to improve measurement accuracy and expand the simulator's functions to allow dynamic simulations.

Masayuki FUJISE

Masayuki Fujise was born in Fukuoka, Japan, on Decenber 8, 1950. He received the B.S., the M.S. and the Dr. Eng. degrees in communication engineering from Kyusyu University, Fukuoka, Japan in 1973, 1975 and 1987, respectively and the M. Eng. degree in electrical engineering from Cornell University, Ithaca, NY, in 1980.

He joined KDD Research & Development Laboratories in 1975. His research activities included optical fiber measurement techniques for Rayleigh scatter, splicing, and chromatic dispersion, and also characterization of optical fibers and semiconductor lasers for optical fiber transmission systems.

Since 1990, he has been with ATR Optical and Radio Communications Research Laboratories as the head of the Radio Communications Department. He is engaged in the research and development for the optical intersatellite communication and active array antenna.

Dr. Fujise is the recipient of the Jack Spergel Memorial Award for the most outstanding technical paper of the 33rd International Wire & Cable Symposium in 1984. He is a member of the IEEE and the IEICE Japan.

Free-Space Simulator for Laser Transmission

Masayuki Fujise

ATR Optical and Radio Comms. Res. Labs.

December 7, 1990

IWOSC '90

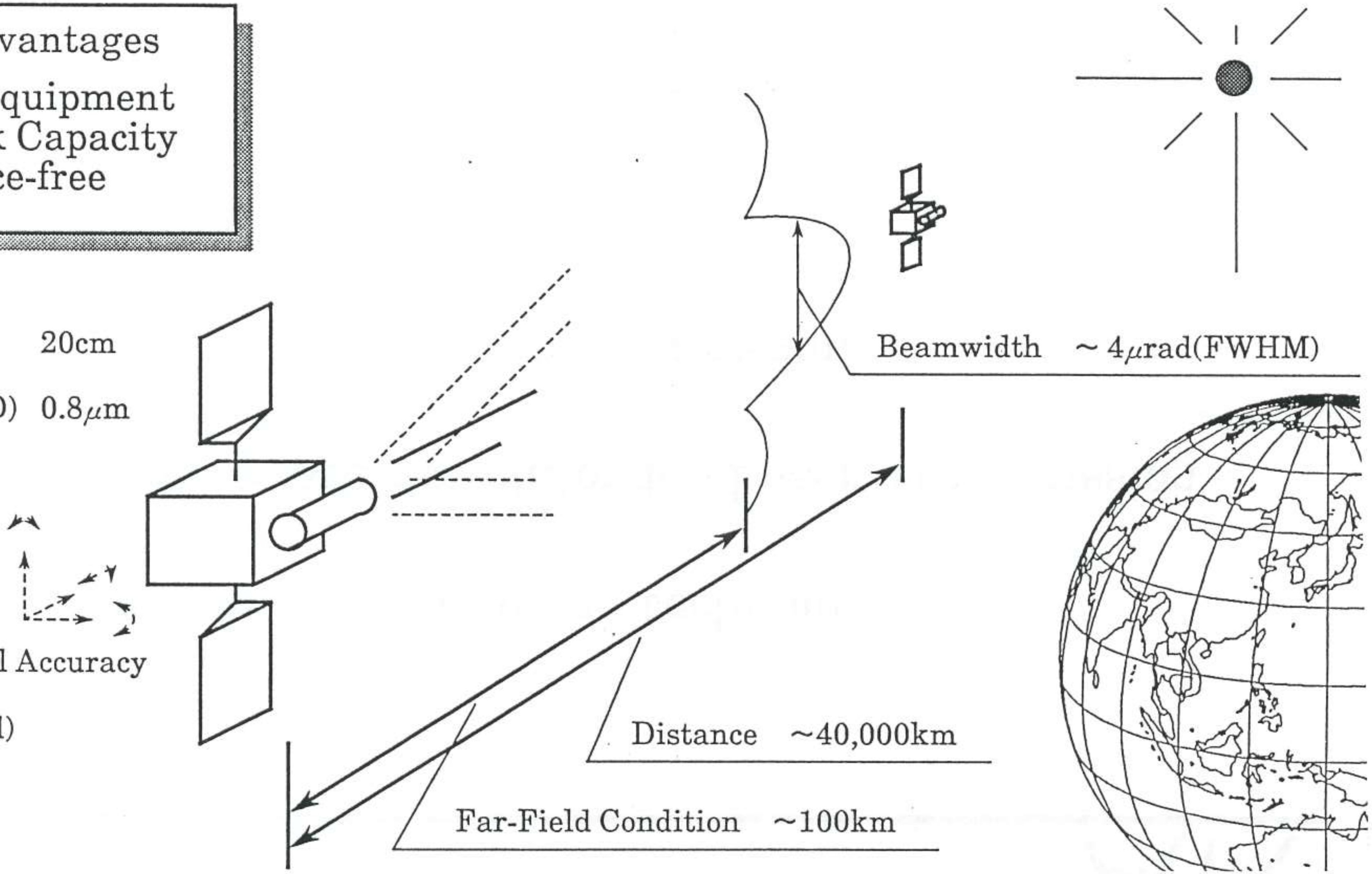
Agenda

1. Optical Beam Control Technology
2. Free-Space Simulator for Laser Transmission
3. Optical Transmitter Estimation
4. Conclusion

Optical ISL System

Potential Advantages

- ·Compact Equipment
- ·Large Link Capacity
- ·Interference-free



Antenna
  Diameter 20cm
Wavelength
  (GaAlAs LD) 0.8μm

Attitude Control Accuracy
±0.1°~0.5°
(±2~10mrad)

Beamwidth ~ 4μrad(FWHM)

Distance ~40,000km

Far-Field Condition ~100km

Optical Beam Control Technology

Functions

- Extremely Low Divergent Beam Shaping
- Pointing / Acquisition / Tracking
- Point Ahead Control

Accuracy

- < μrad

Evaluation Methods

ESA・
カナリー諸島の実験:

Space to ground
measurement

Near Field Approach

- Test Bed Systems in Laboratory

– Not Actually Implementated of Far Field

Open Range Approach

- GEO-ground Measurement (CRL/LCE)
- Intermountain Test (ESA)
- Stratospheric Ballons Experiment (Dornier)

– Difficult to Perform

Germany

Compact Range Approach

ATR

Diffraction Theory

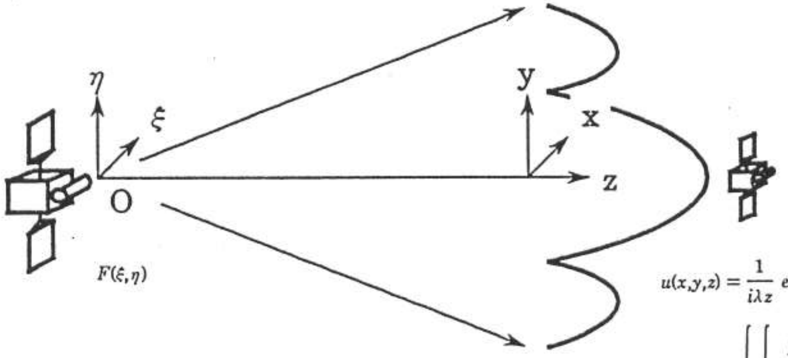
Fraunhofer Diffraction

$$u(x,y,z)=\frac{1}{i\lambda z}\,exp\left[ik\frac{x^2+y^2}{2z}\right]\iint_A u_0(\xi,\eta)\,exp\left[-ik\left(\frac{x\xi+y\eta}{z}\right)\right]d\xi\,d\eta$$

Fresnel Diffraction

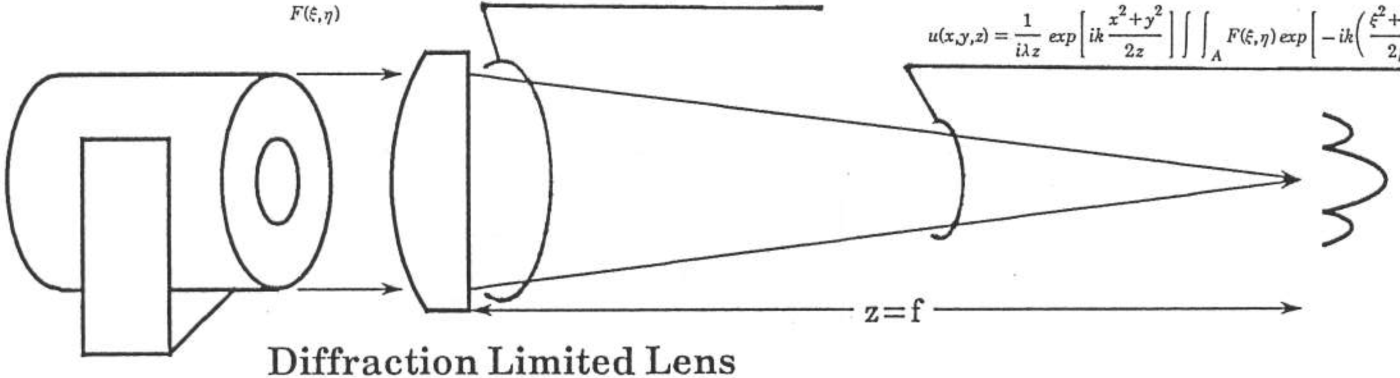
$$u(x,y,z)=\frac{1}{i\lambda z}\,exp\left[ik\frac{x^2+y^2}{2z}\right]\iint_A u_0(\xi,\eta)\,exp\left[-ik\left(\frac{x\xi+y\eta}{z}-\frac{\xi^2+\eta^2}{2z}\right)\right]d\xi\,d\eta$$

Far-Field



$$u(x,y,z)=\frac{1}{i\lambda z}\,exp\left[ik\frac{x^2+y^2}{2z}\right]\iint_A F(\xi,\eta)\,exp\left[-ik\left(\frac{x\xi+y\eta}{z}\right)\right]d\xi\,d\eta$$

Compact Range



$$u_0(\xi,\eta)=F(\xi,\eta)\,exp\left[-ik\left(\frac{\xi^2+\eta^2}{2f}\right)\right]$$

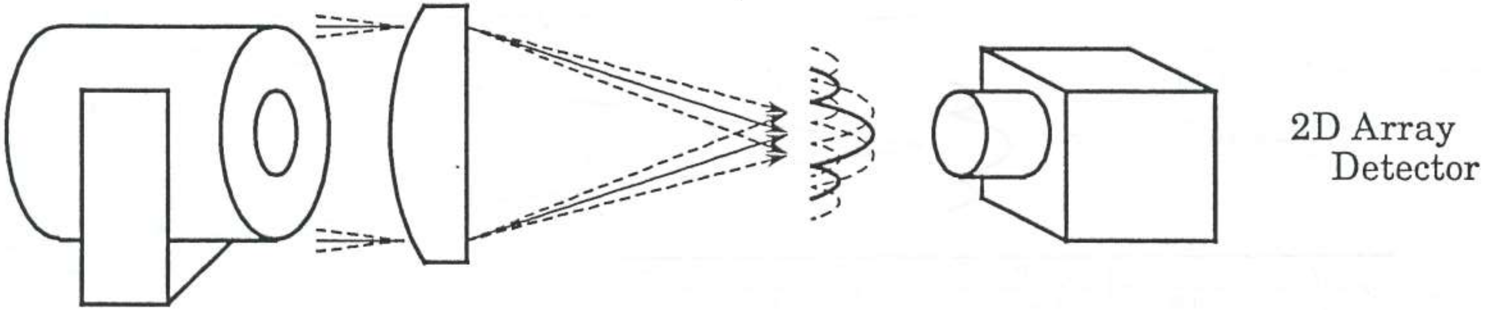
$$u(x,y,z)=\frac{1}{i\lambda z}\,exp\left[ik\frac{x^2+y^2}{2z}\right]\iint_A F(\xi,\eta)\,exp\left[-ik\left(\frac{\xi^2+\eta^2}{2f}\right)\right]exp\left[-ik\left(\frac{x\xi+y\eta}{z}-\frac{\xi^2+\eta^2}{2z}\right)\right]d\xi\,d\eta$$

$$u(x,y,z=f)=\frac{1}{i\lambda f}\,exp\left[ik\frac{x^2+y^2}{2f}\right]\iint_A F(\xi,\eta)\,exp\left[-ik\frac{x\xi+y\eta}{f}\right]d\xi\,d\eta$$

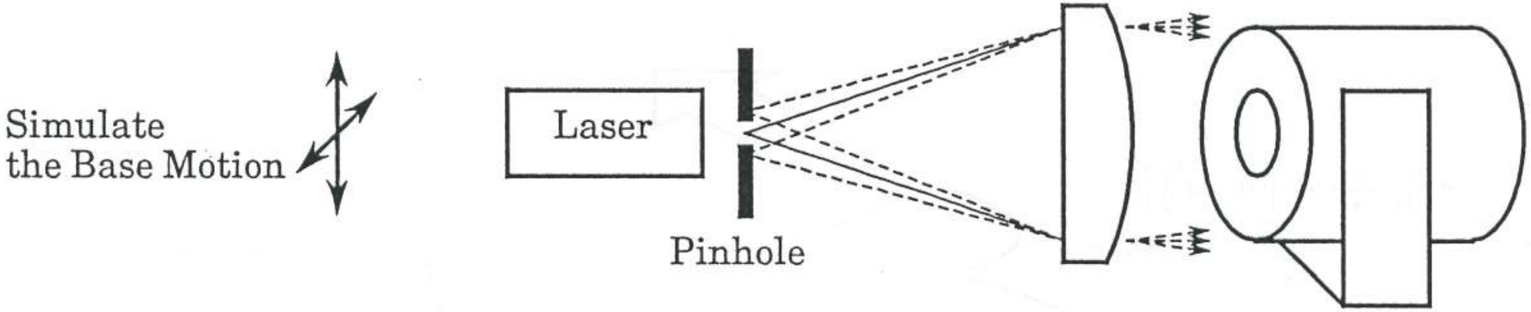
Diffraction Limited Lens

Dynamic Simulations

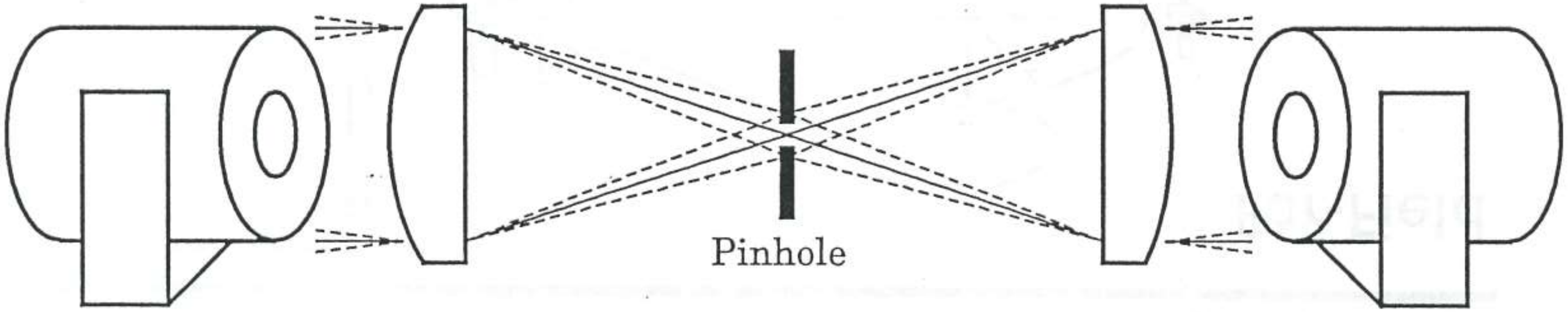
- Pointing



- Tracking



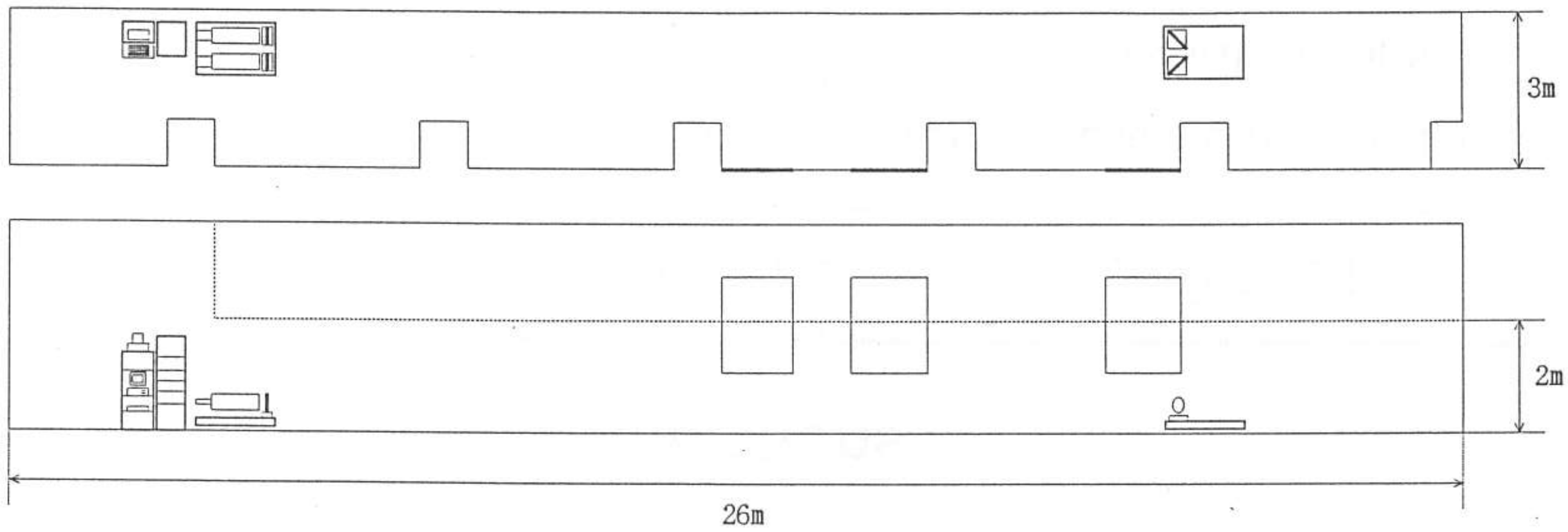
- Bidirectional
  Pointing/Tracking

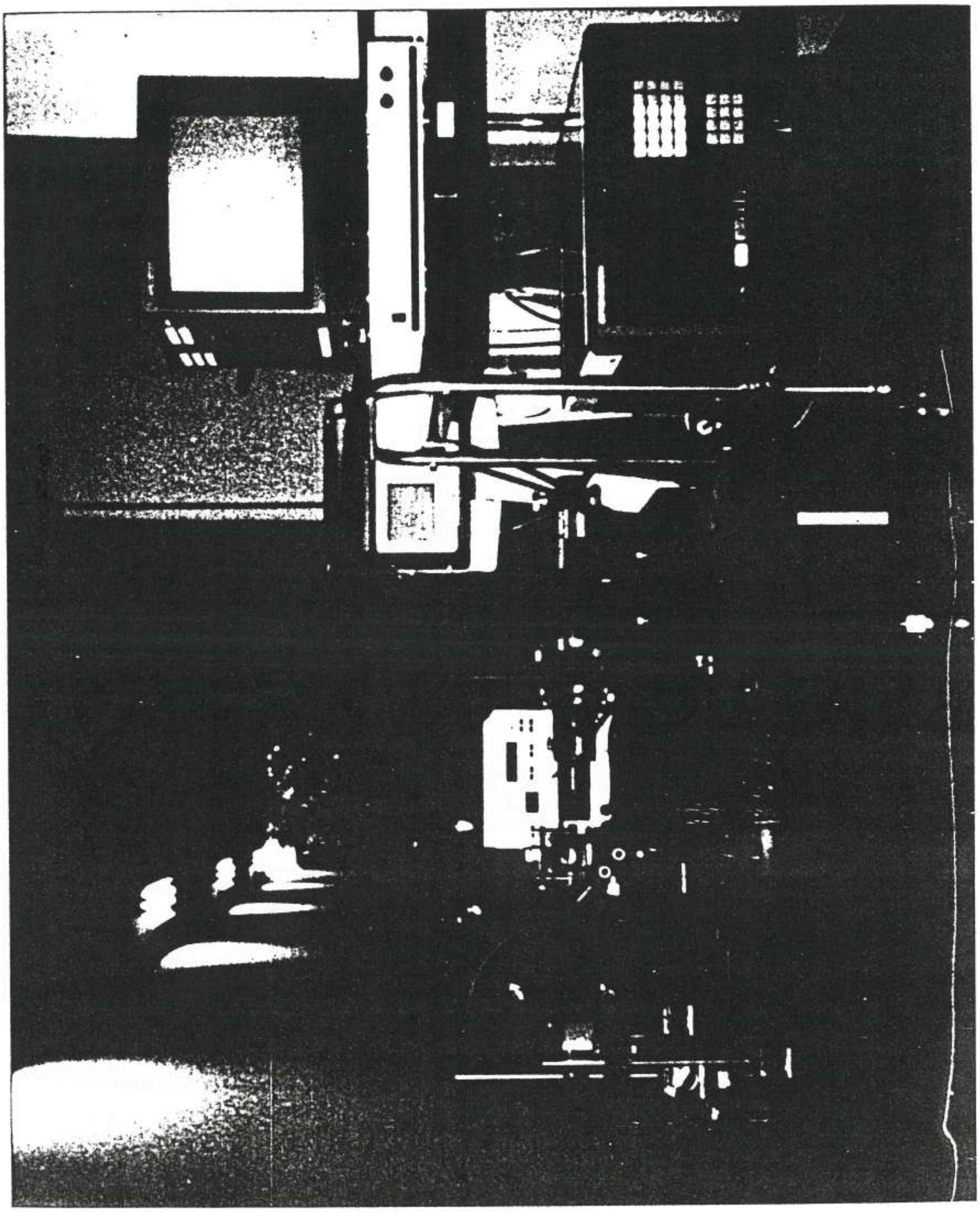


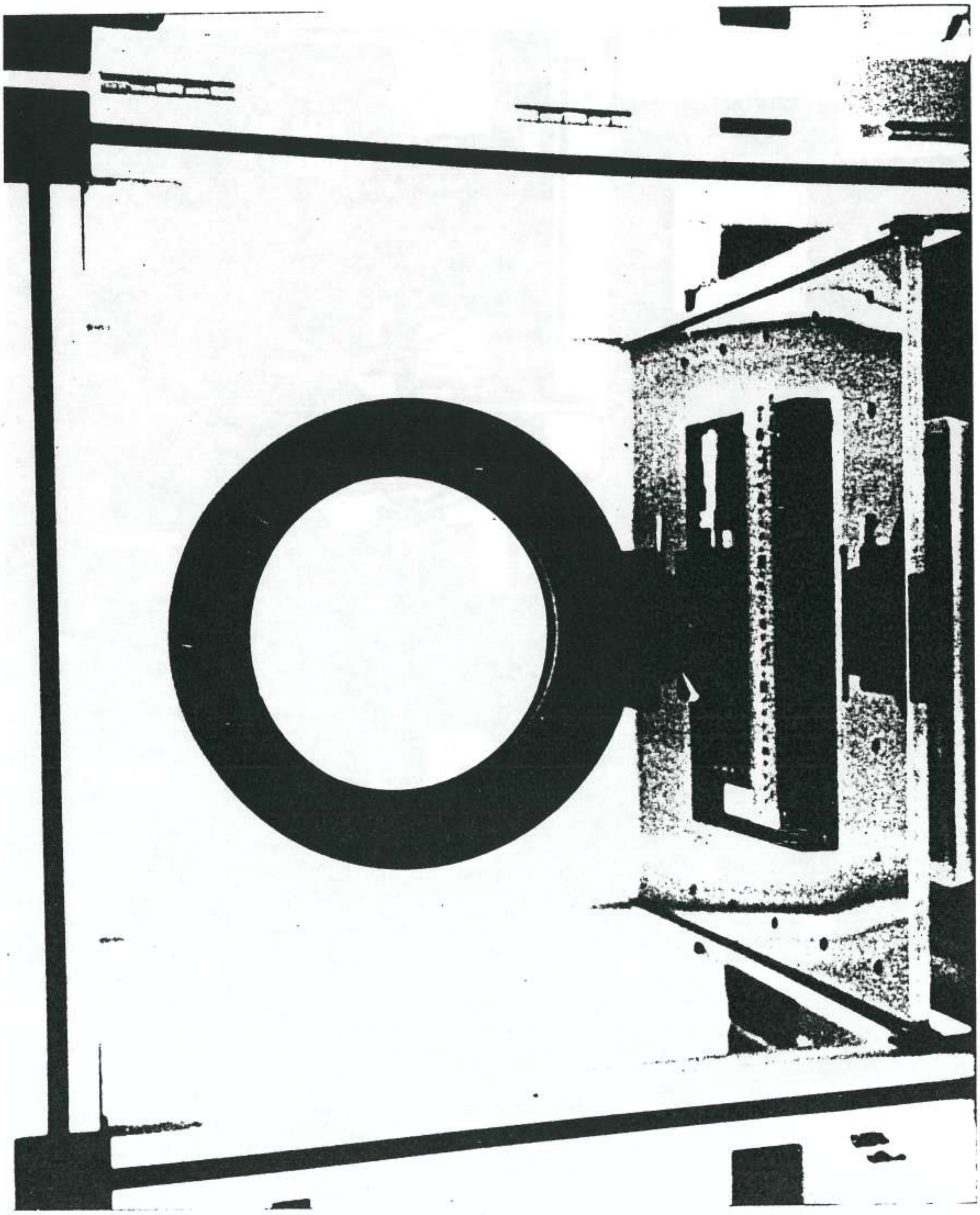
Functions

Item	Simulation Function	Method
Antenna Performance	Tx:FFP Implementation Rx:Ideal Beam Formation in Large Diameter	A Large Aperture Diffraction Limited Lens The Lens and a Point Source
Pointing	High-Speed FFP Measurement	2D Array Detector
Tracking	Direction Control of the Beam	Position Control of Point Source
Bidirectional Pointing/Tracking	Mutual Coupling between Pointing/Tracking Errors	A Pair of Lenses and a Pinhole

Simulator Configulation







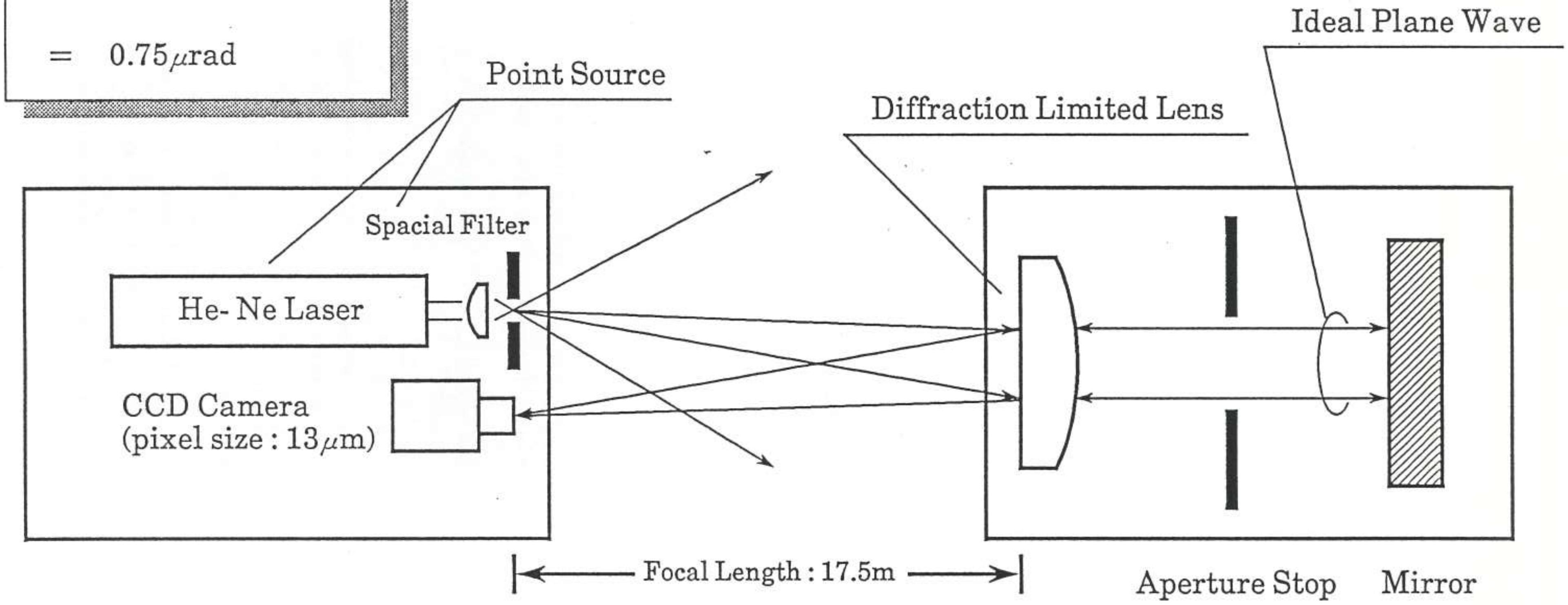
FFP Implementation Test

Angular Resolution

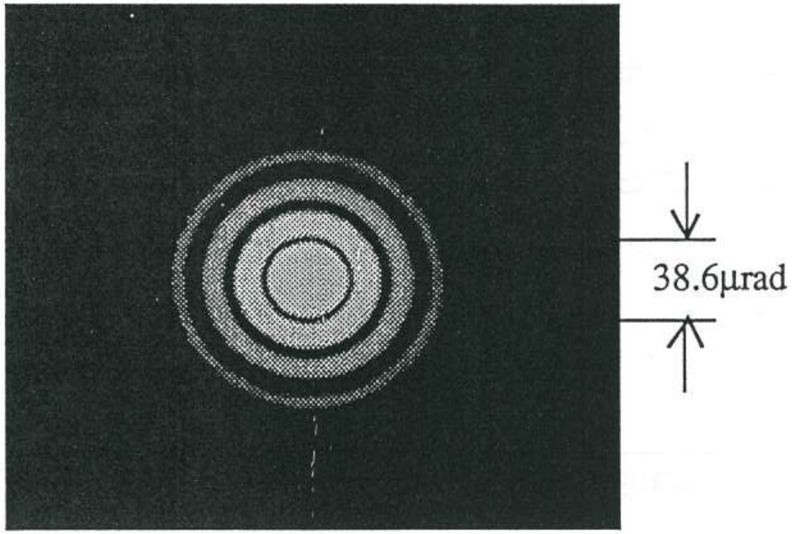
$$= \frac{\text{CCD Pixel Size}}{\text{Focal Length}}$$

$$= 0.75\mu\text{rad}$$

Experimental Setup

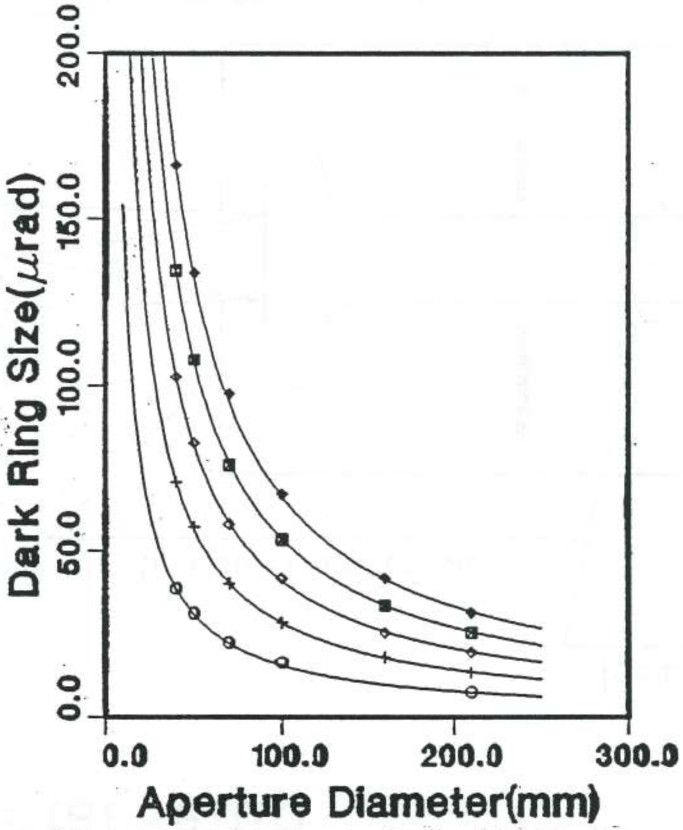


FFP Implementaion Test



Airy Pattern

(The Case of ϕ40mm)

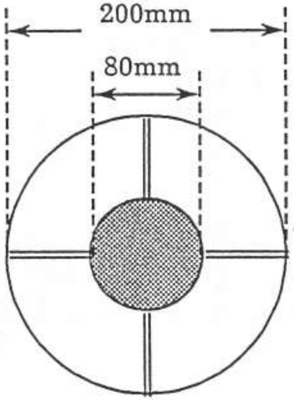


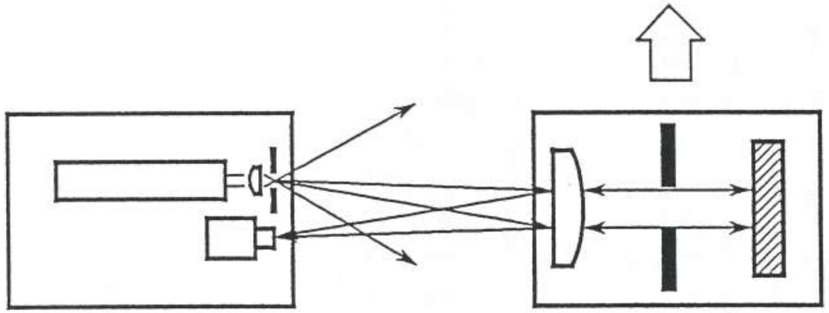
Measurements and Theoretical Curves

FFP in Reference Optical System

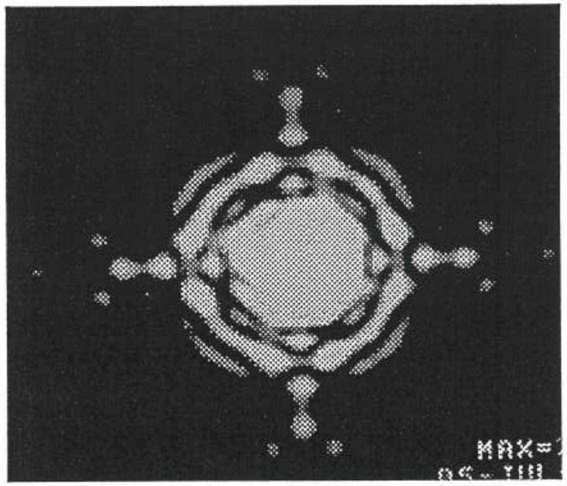
ATR

Mask Pattern
= Aperture Form of
the Optical Antenna

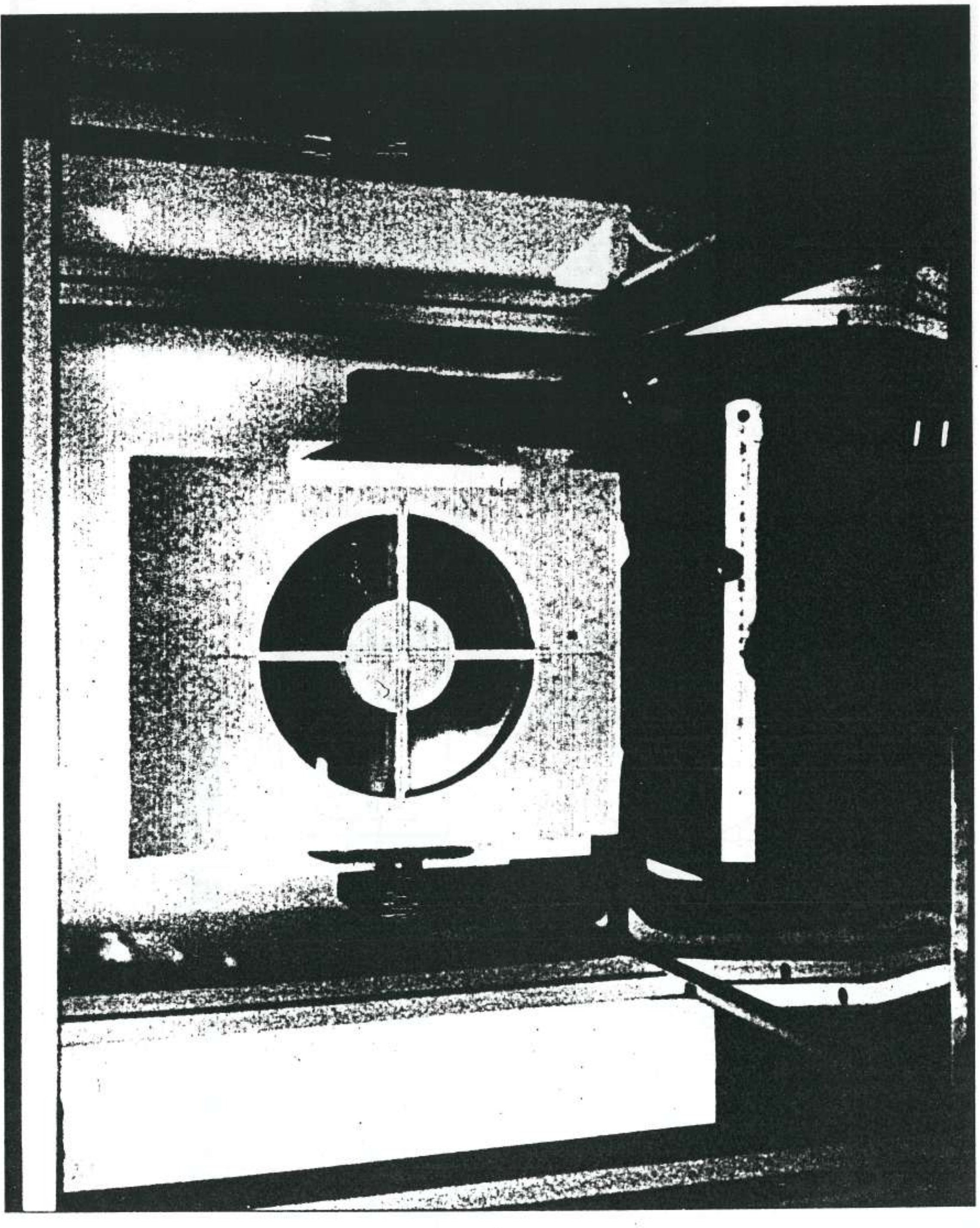




Experimental Setup



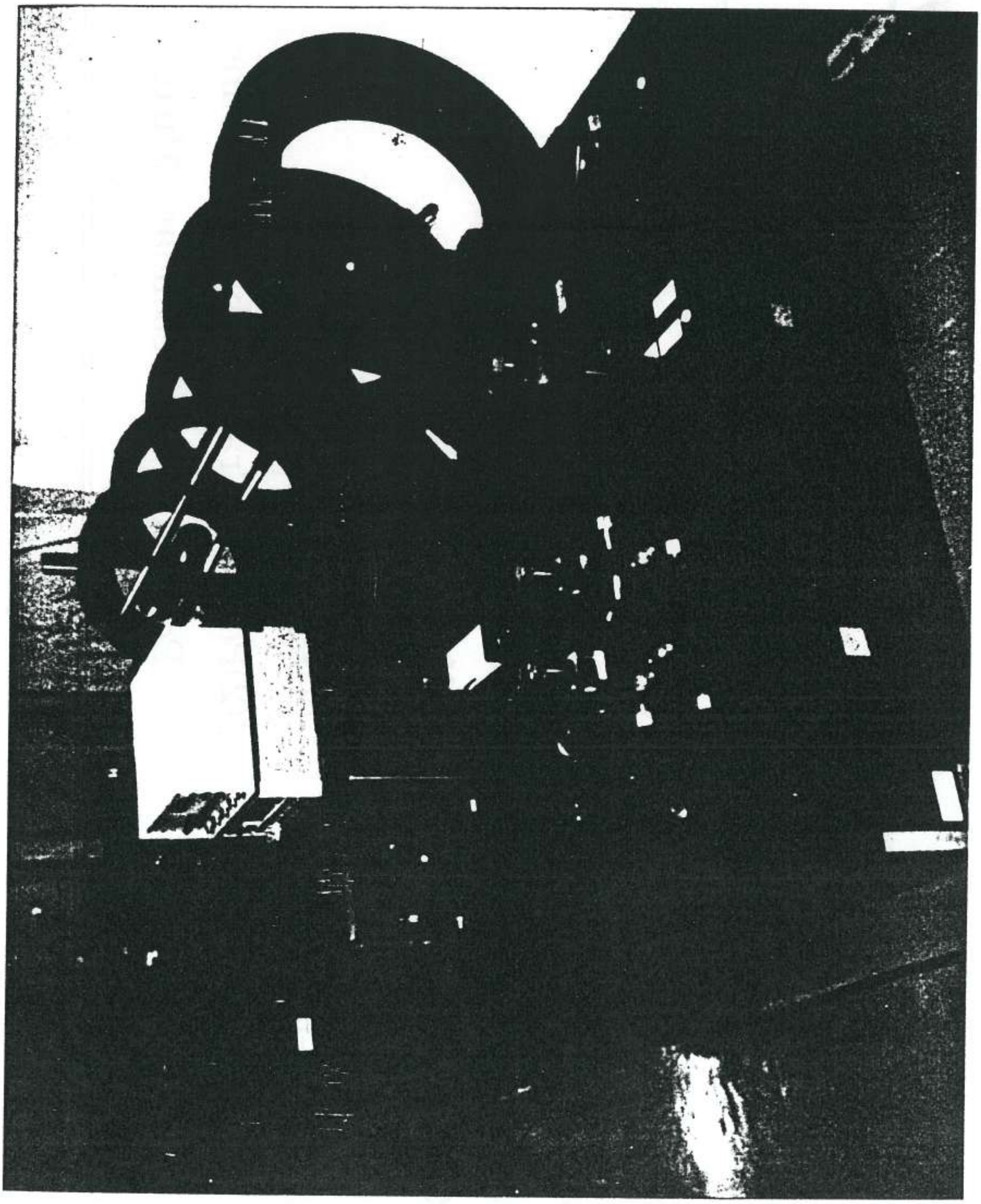
FFP



Optical Antenna

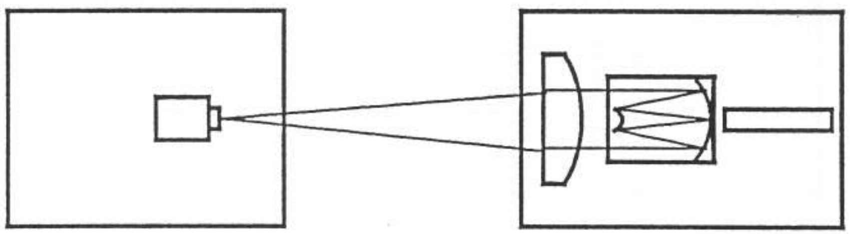
Specifications

Type	Center Feed Cassegrain Telescope
Aperture Diameter	200mm (Primary Mirror)
Focal Length	2.4m, F=12
Overall Dimensions	360(W)x380(H)x900(L)
Weight	18kg
Special Features	(1)Supported by Invar Rods (2)Pointing/Tracking by Controlling Position of the Secondary Mirror

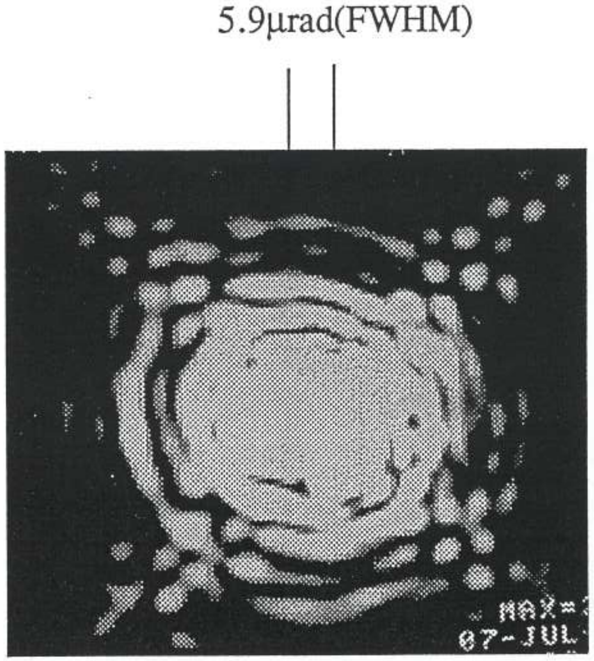


FFP by Opt. Antenna+He-Ne

Source: He-Ne Laser
+ Spatial Filter



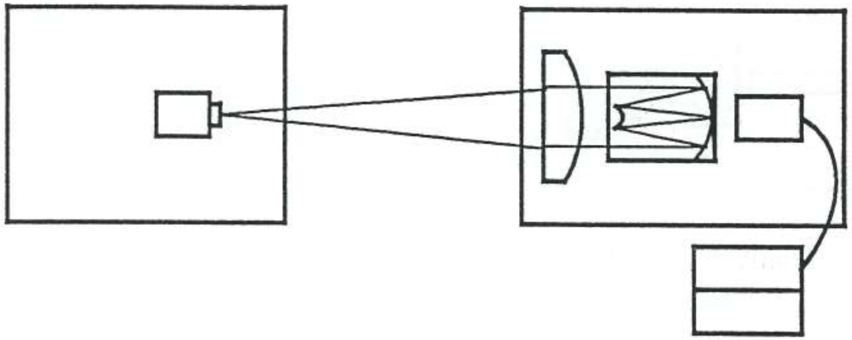
Experimental Setup



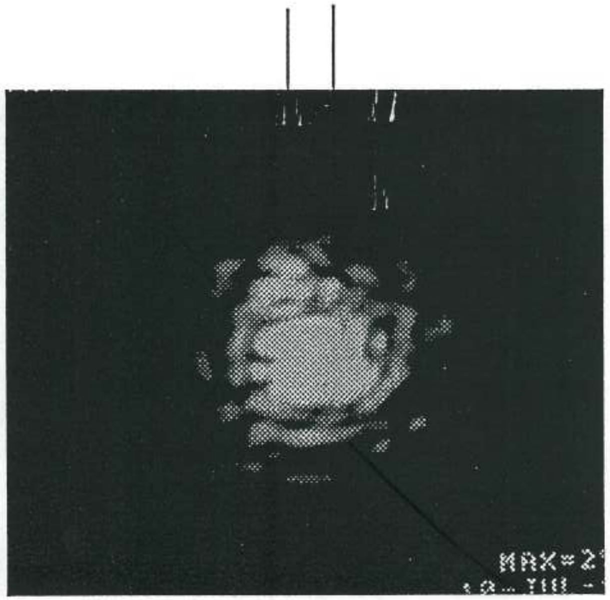
FFP

FFP by Opt. Antenna+LD

Source: High-power LD
(30mW, cw)



Experimental Setup

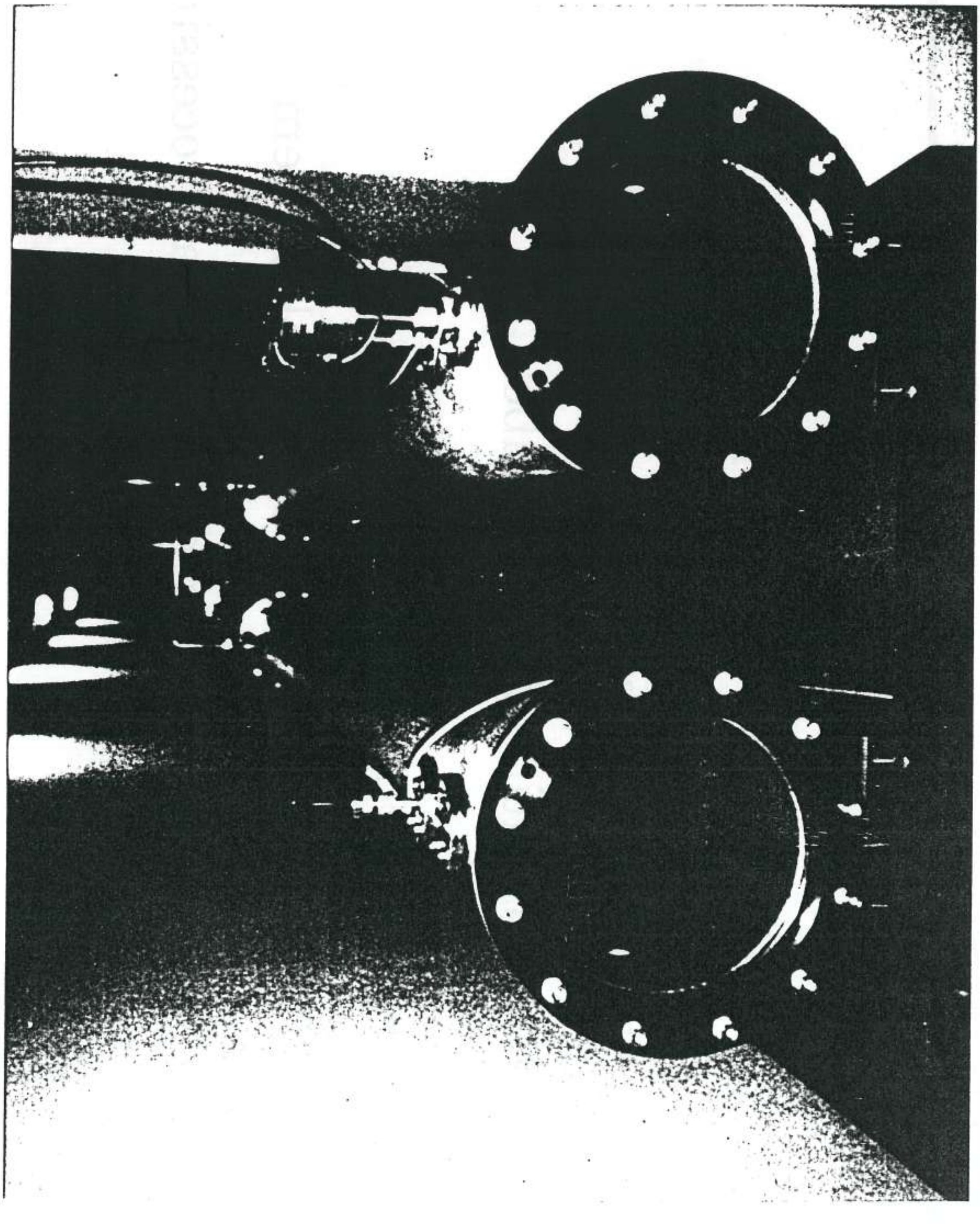


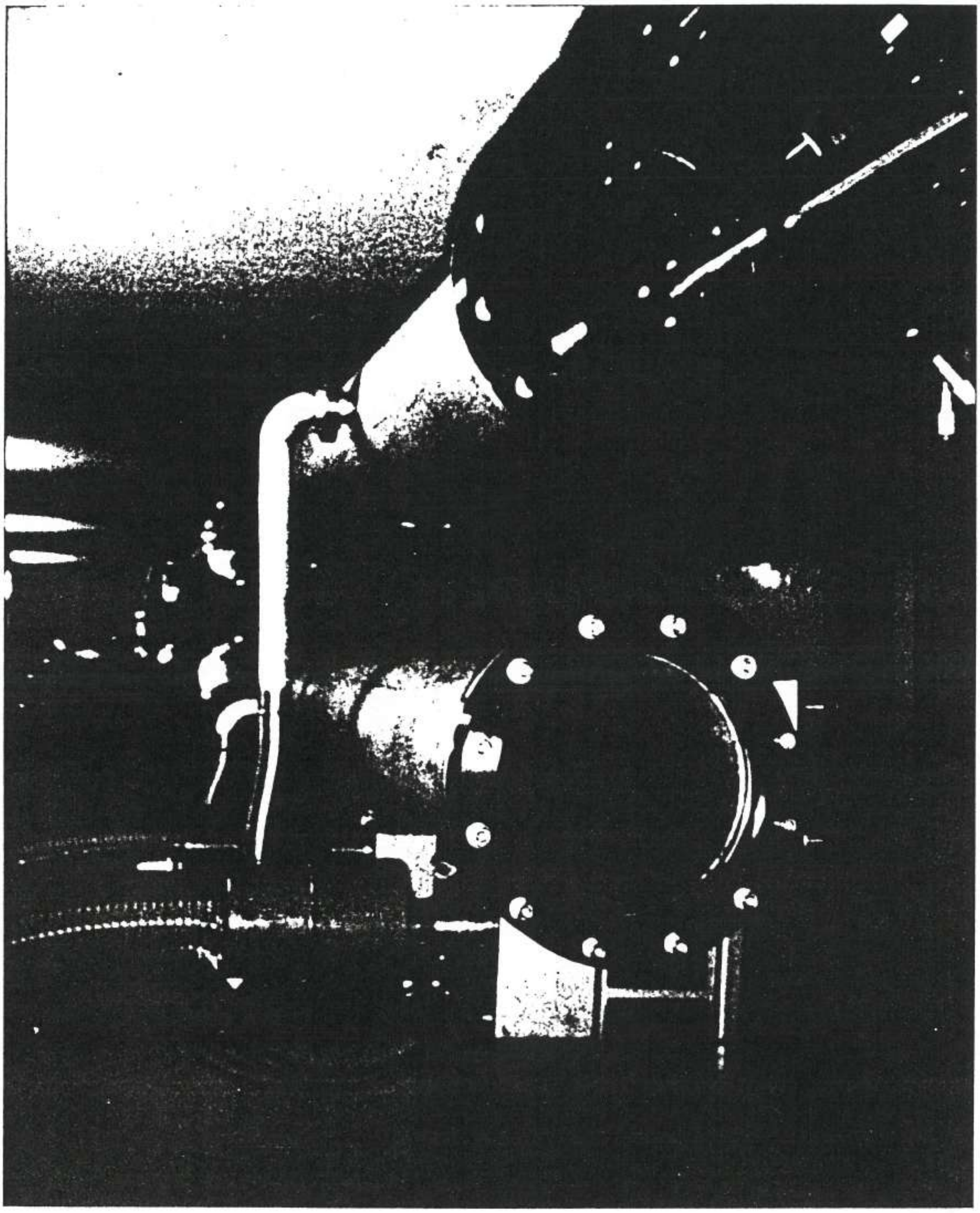
FFP

Measurement Errors

Identification of Major Errors

1. Atmospheric Turburance
    - Scintillation-free Chamber
2. Environmental Vibration
    - Vibration-insensitive Optical System
    - Vibration Monitoring and Data Processing





Future Work

1. Improve the Measurement Accuracy by Conquering Environmental Disturvances

b

2. Expand the Simulator's Function to Allow Dynamic Simulations

Conclusion

Free-Space Simulator for Laser Transmission

1. We proposed a "Free-Space Simulator for Laser Transmission" to evaluate optical beam control subsystems.
2. The results of the FFP implementation test has shown that the simulator under development can achieve the accuracy of μrad ord~~a~~er.
3. This simulation technique has a potential to estimate the actual transmitted effective power.

4-2

Effect of microaccelerations on an optical space communication system

Manfred E. Wittig

ESA
ESTEC

IWOSC '90
December 6 and 7, 1990, ATR, Kyoto

Effect of Microaccelerations on an Optical Space Communication System

M. Wittig
ESA/ESTEC Noordwijk, The Netherlands

Abstract

Future laser intersatellite communication links are planned which will have beamwidths in the arc second range and below. The performance, and even the feasibility of such links, depends heavily upon the mechanical vibrations induced into the optical terminals by the host satellite(s). In particular, it is important to know the level of microvibrations on a spacecraft for the design of the tracking control loop of an optical communication payload.

The first in-orbit measurements of microvibrations on-board a satellite were taken on Landsat and were published in 1984. These were used to derive a worst case envelope of vibration power spectral density. The published curve, however, terminated abruptly at 125 Hz, caused by the limited bandwidth of the measurement device.

As a consequence of this limited knowledge and the importance of the subject for the performance of an optical communication system, ESA decided to install microaccelerometers to be embarked as an experiment on its large communication satellite, OLYMPUS.

The aim of this experiment was to characterise and observe the induced vibration behaviour of the different spacecraft mechanisms in space and to obtain measurements of the vibration levels which are of relevance for the design of optical communication payloads.

OLYMPUS was launched in July 1989. During the commissioning phase of the spacecraft, in August/September 1989, a large number of accelerometer data recordings were made at ESTEC.

The translation of the measured acceleration spectra into a base motion spectra showed a higher amount of vibration in the frequency region above 100 Hz, when compared with previously reported data from Landsat spacecraft.

The most disturbing vibration sources, solar array drive and thruster firing, can not be characterised precisely enough by on ground measurements. This confirms that measurements in space are mandatory before flying an optical payload.

An attempt to optimise the tracking control loop of an optical communication payload, taking into account the different sources of pointing error, such as detector noise and microvibrations, will also be presented.

In any event, the curve related to the specific design of LANDSAT, and hence could not be considered a reliable assessment of the situation in general.

Curriculum vitae **Manfred Wittig**

Manfred Wittig was born in 1951 in Hameln, West-Germany.
He studied communications engineering at the Technical University in Berlin.
He worked in industry in the field of biomedical electronics and in the Heinrich-Hertz-Institute for Communication Engineering in the two-way cable TV-project.
In 1980 he joined the Institute for Aerospace Engineering of the Technical University Berlin where he worked in the field of optical communication and navigation.
In 1983 he joined the Institute of Navigation of the University Stuttgart and continued working on optical communication and navigation. He got the PhD from Stuttgart University with a thesis about improvement of navigation systems.
In 1986 he joined the Battelle Institute in Frankfurt as a research scientist working in the field of optical communication.
In 1987 he joined ESA/ESTEC in Norrdwijk as a principal optical payload system engineer.

Effect of Microaccelerations on an Optical Space Communication System

Manfred Wittig

Communication Payload Section
CSP

*****

ESTEC - European Space Research and Technology Centre
of

ESA - European Space Agency

Noordwijk/The Netherlands

*****

Prepared for the

International Workshop on
Optical Space Communication
IWSOC '90

IWSOC '90
Dec. 7th 1990
Kyoto

Effect of Microaccelerations on an Optical Space Communication System

OVERVIEW

- * INFLUENCE OF POINTING ERRORS ON LINK QUALITY
- * MICROVIBRATIONS FROM HOST SPACECRAFT
- * PAX
- * TRANSFER OF MICROVIBRATIONS BY STRUCTURE
- * OPTIMIZATION OF CONTROL LOOP
- * CONCLUSION

IWSOC '90
Dec. 7th 1990
Kyoto

Effect of Microaccelerations on an Optical Space Communication System

* **INFLUENCE OF POINTING ERRORS ON LINK QUALITY**
* MICROVIBRATIONS FROM HOST SPACECRAFT
* PAX
* TRANSFER OF MICROVIBRATIONS BY STRUCTURE
* OPTIMIZATION OF CONTROL LOOP

IWSOC ’90
Dec. 7th 1990
Kyoto

Link Budget

The received power P_r is proportional to the power flux density and the collecting aperture A_r

$$P_r := \frac{P_t \cdot G_t(\delta,\Phi)}{4 \cdot \pi \cdot R^2} \cdot A_r$$

The power flux density is a function of the

- transmitter power P_t
- transmit antenna gain $G_t(\delta,\Phi)$
- distance R

Any pointing error reduces the received power.
This reduction is given by the antenna radiation pattern.

Effect of Microaccelerations on an Optical Space Communication System

Antenna Radiation Far Field Pattern

Ideal Radiating Circular Aperture

$$G := \left[\pi \cdot \frac{D}{\lambda}\right]^2 \cdot \left[2 \cdot \frac{J1\left[\pi \cdot \frac{D}{\lambda} \cdot \epsilon\right]}{\pi \cdot \frac{D}{\lambda} \cdot \epsilon}\right]^2$$

Gaussian Beam

$$G := \left[2 \cdot \pi \cdot \frac{w}{\lambda}\right]^2 \cdot e^{-\left[2 \cdot \pi \cdot \frac{\epsilon}{\lambda}\right]^2}$$

Real Radiating Circular Aperture
with Gaussian Beam as Input

$$G := \left[\pi \cdot \frac{D}{\lambda}\right]^2 \cdot 2 \cdot \alpha^2 \cdot \left\|\int_{\Gamma^2}^{1} e^{-\left[\alpha^2 \cdot u\right]} \cdot e^{j(\delta \cdot u)} \cdot J0\left[X(\epsilon) \cdot \sqrt{u}\right] \, du\right\|^2$$

Effect of Microaccelerations on an Optical Space Communication System

Pointing error ϵ

$$\alpha := 1.12 - 1.23 \cdot \Gamma^{2} + 2.12 \cdot \Gamma^{4}$$

Beam waist $\omega := \frac{D}{\alpha}$

Obscuration ratio $\Gamma := \frac{b}{D}$

Secondary mirror diameter b

Defocussing parameter $\delta := 2 \cdot \frac{\pi}{\lambda} \cdot D^{2} \cdot \left[\frac{1}{r1} + \frac{1}{R}\right]$

Curvature of wavefront $r1$

Link distance R

$$X(\epsilon) := 2 \cdot \frac{\pi}{\lambda} \cdot D \cdot \sin(\epsilon)$$

Effect of Microaccelerations on an Optical Space Communication System

Ant. gain.

Far Field Gain Distribution in dB

Ideal Gain

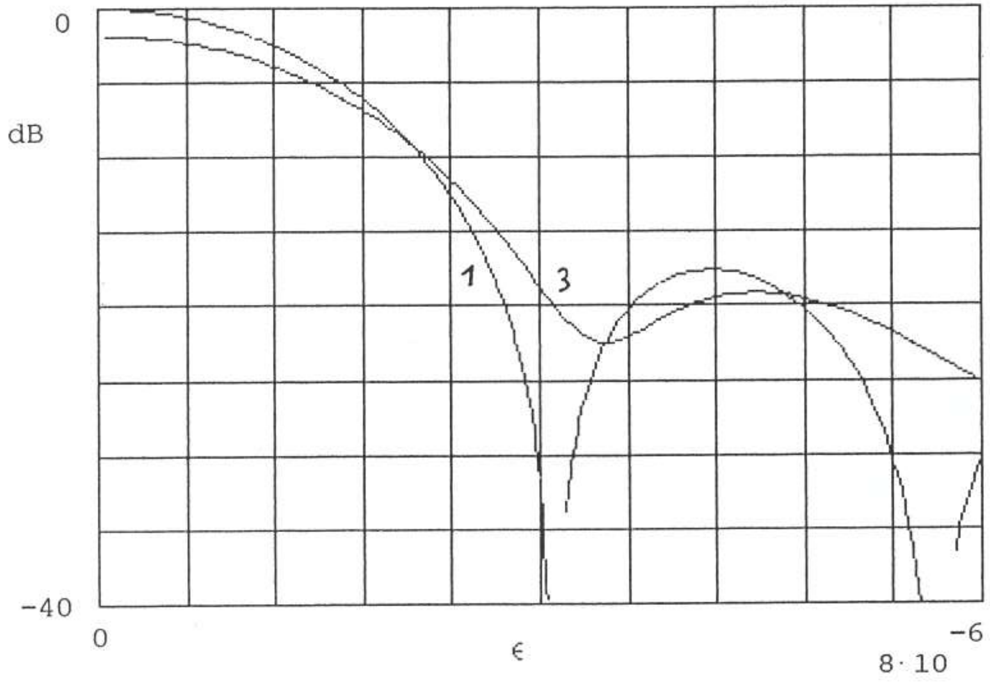
$G1 = 119.344$

in dB

$\epsilon = 0.984$

Distance =

$R_{km} = 4.5 \cdot 10^{4}$



$$gT\left[0 \cdot 10^{-6}\right] = -1.8$$

$$gT\left[1 \cdot 10^{-6}\right] = -2.613$$

$$gT\left[2 \cdot 10^{-6}\right] = -5.194$$

$$gT\left[3 \cdot 10^{-6}\right] = -10.111$$

$$gT\left[4 \cdot 10^{-6}\right] = -18.652$$

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Pointing Error Statistic

Gaussian distribution of pointing error around x and y axis

$$f_x := \frac{1}{\sqrt{2\cdot\pi}\cdot\sigma}\cdot e^{-\left[\frac{x^2}{2\cdot\sigma^2}\right]}$$

Resulting Rayleigh distribution of radial pointing error ϵ

$$f_z := \frac{z}{\sigma^2}\cdot e^{-\left[\frac{z^2}{2\cdot\sigma^2}\right]}$$

Probability of exceeding the pointing error ϵ

$$P\left[f_z > \epsilon\right] := \frac{\epsilon}{\sigma^2}\cdot e^{-\left[\frac{\epsilon^2}{2\cdot\sigma^2}\right]}$$

Effect of Microaccelerations on an Optical Space Communication System

If a probability of exceeding a pointing error ϵ is specified as P_b (also known as Burst Error Probability) we require

$$\epsilon < \epsilon_m + \sigma \cdot \sqrt{-2 \cdot \ln\left[P_b\right]}$$

if we add a bias term ϵ_m

The goal is to minimize σ

Effect of Microaccelerations on an Optical Space Communication System

- INFLUENCE OF POINTING ERRORS ON LINK QUALITY
- **MICROVIBRATIONS FROM HOST SPACECRAFT**
- PAX
- TRANSFER OF MICROVIBRATIONS BY STRUCTURE
- OPTIMIZATION OF CONTROL LOOP

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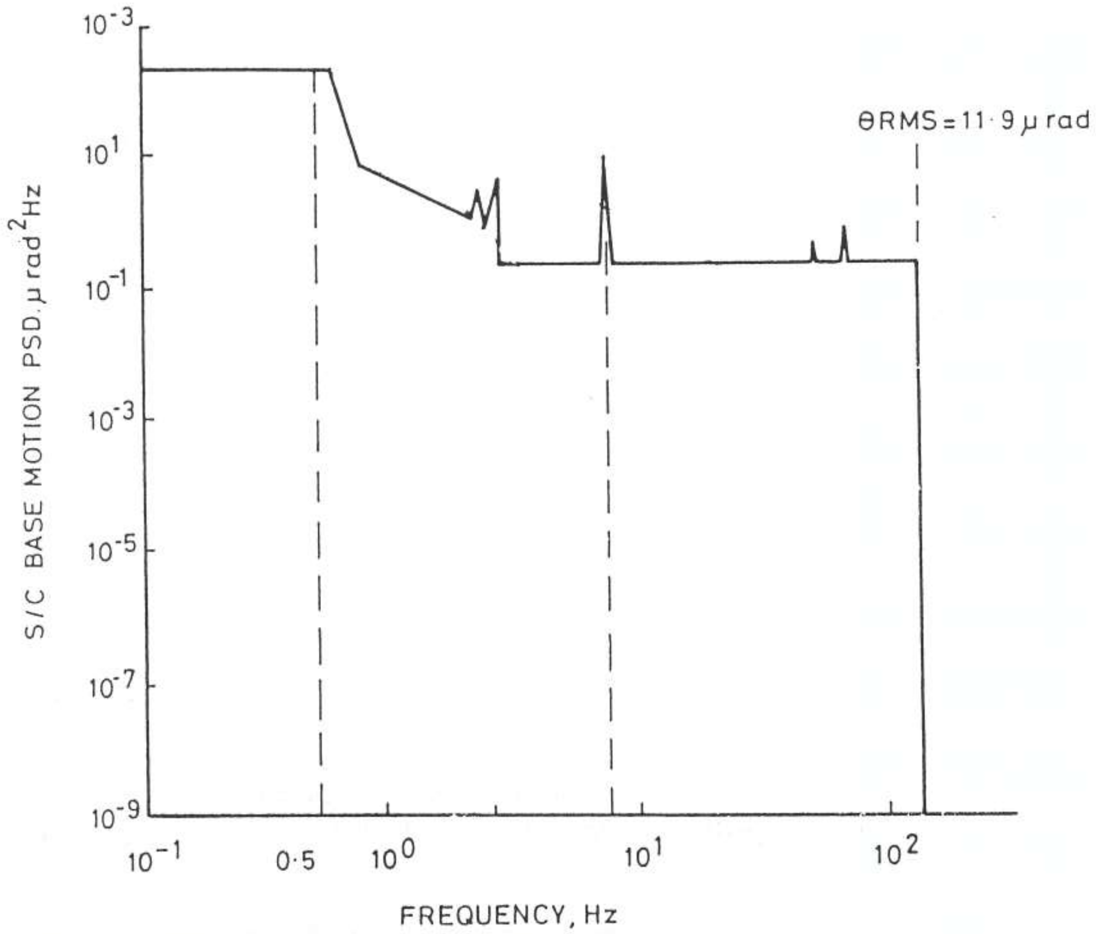
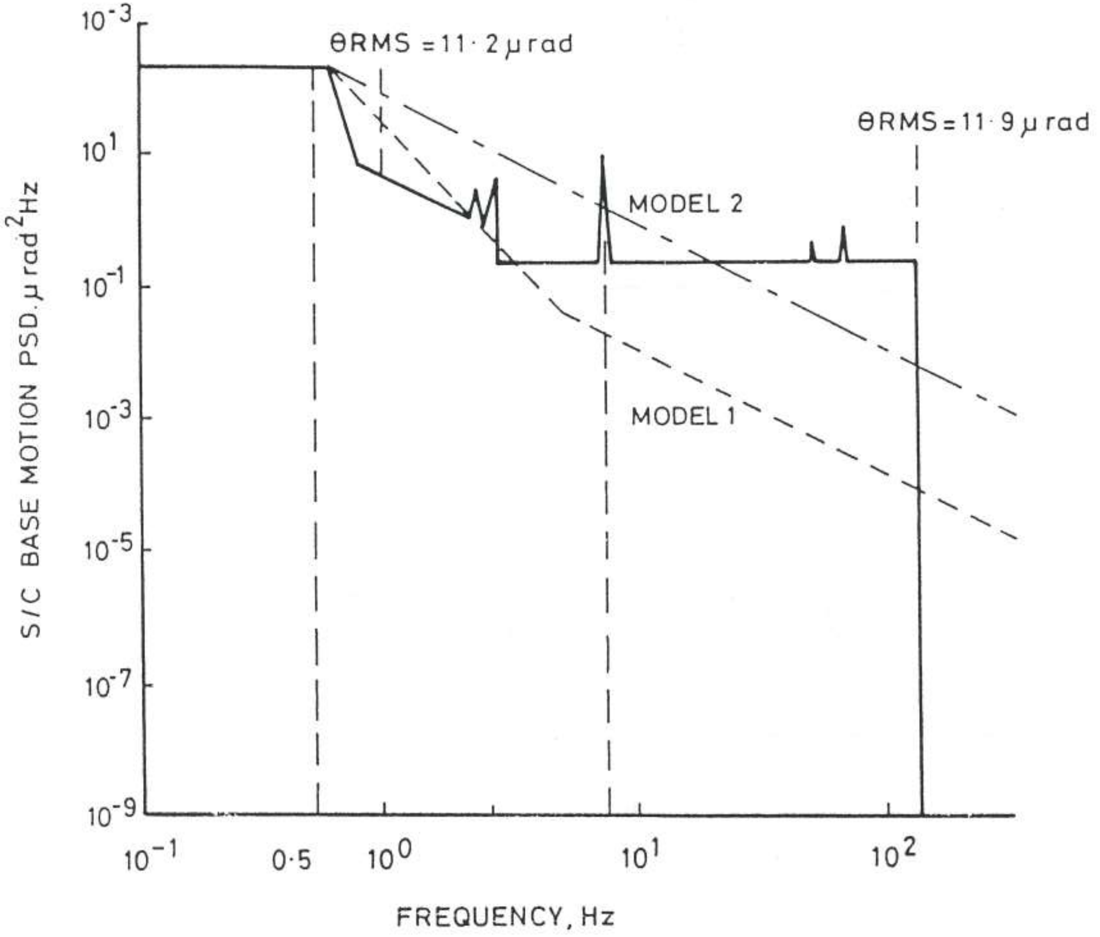
Original Published Disturbance Spectrum obtained from LANDSAT Measurements



Effect of Microaccelerations on an Optical Space Communication System

Continous Approximation of the LANDSAT Curve



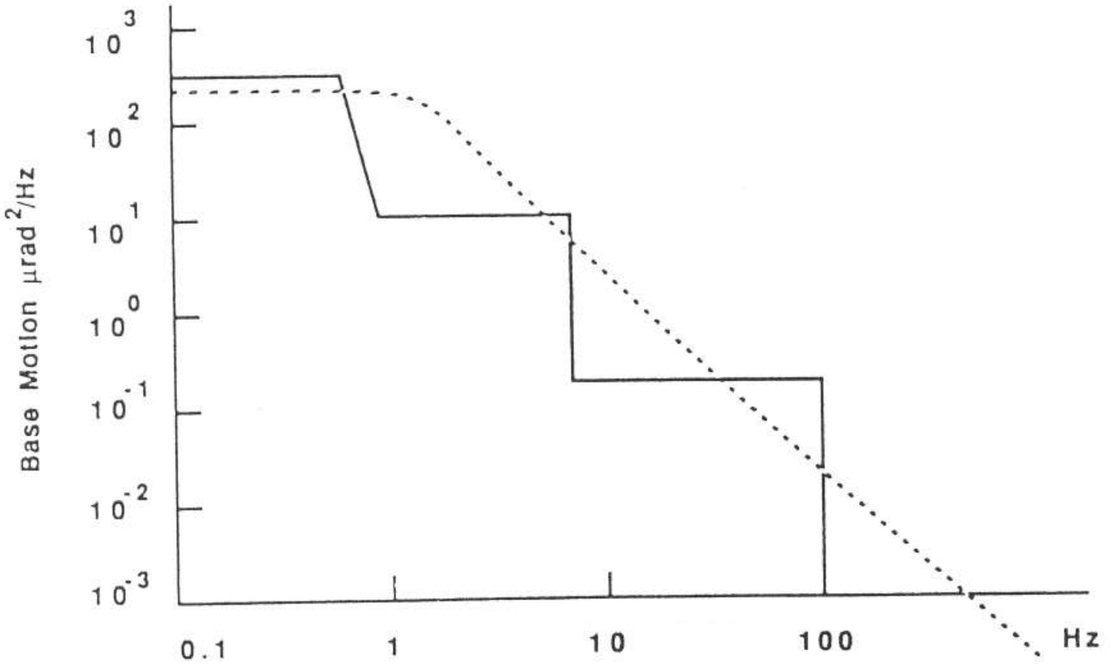
Olympus!

reaction wheel

(not momentum wheel)

TDS

ESA's Specification



Olympus.
the largest satellite
ever launched.

Effect of Microaccelerations on an Optical Space Communication System

esa

- * INFLUENCE OF POINTING ERRORS ON LINK QUALITY
- * MICROVIBRATIONS FROM HOST SPACECRAFT
- * **PAX**
- * TRANSFER OF MICROVIBRATIONS BY STRUCTURE
- * OPTIMIZATION OF CONTROL LOOP

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PAX EQUIPMENT

WEIGHT : 2.370 Kg

POWER CONSUMPTON : 6.3 W Nominal mode
0.3 W Standby mode

ACCELEROMETER PERFORMANCES

frequency bandwith :0.5 Hz to 1 KHz

full scale (coarse mode) : +/−100 mg
full scale (fine mode) : +/−10 mg
resolution(coarse mode) :50 ug
resolution(fine mode) :5 ug

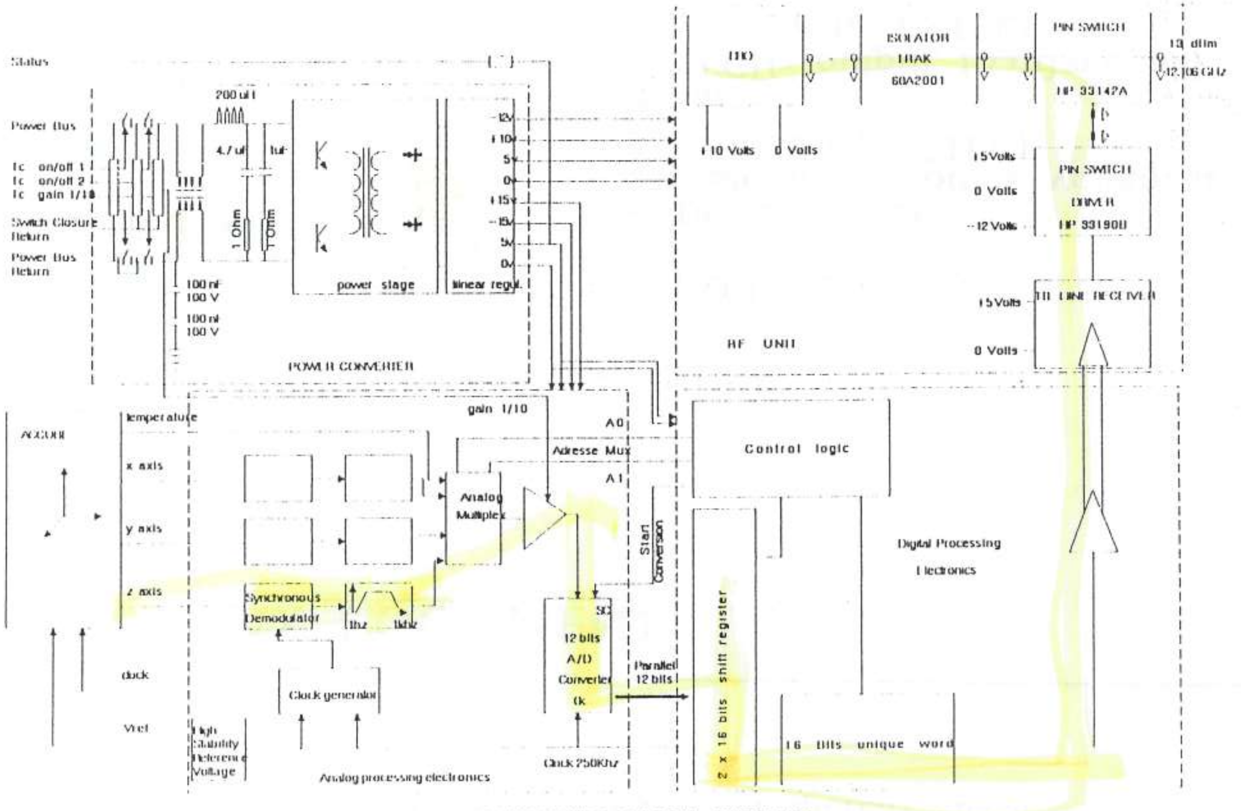
initial accuracy :0.1dB

DESCRIPTION

5 FUNCTIONNAL BLOCKS

- DC/DC Converter
  (50 Volts input, 6 output voltages)
  (Designed by ESTEC)
- RF part
  (12.1 GHz output, 13 dBm peak)
  (Designed by ESTEC)
- Analog processing electronics
  (analog interfaces with Accube)
  (Designed by MATRA)
- ACCUBE (accelerometer cube)
  (3 axis + temperature)
  (Designed by MATRA)
- Digital processing electronics
  (encoding of 3 acceleration informations +)
  (temperature in one unique 80 bits word)
  (Designed by ESTEC)

Effect of Microaccelerations on an Optical Space Communication System



EQUIPMENT BLOCK DIAGRAM

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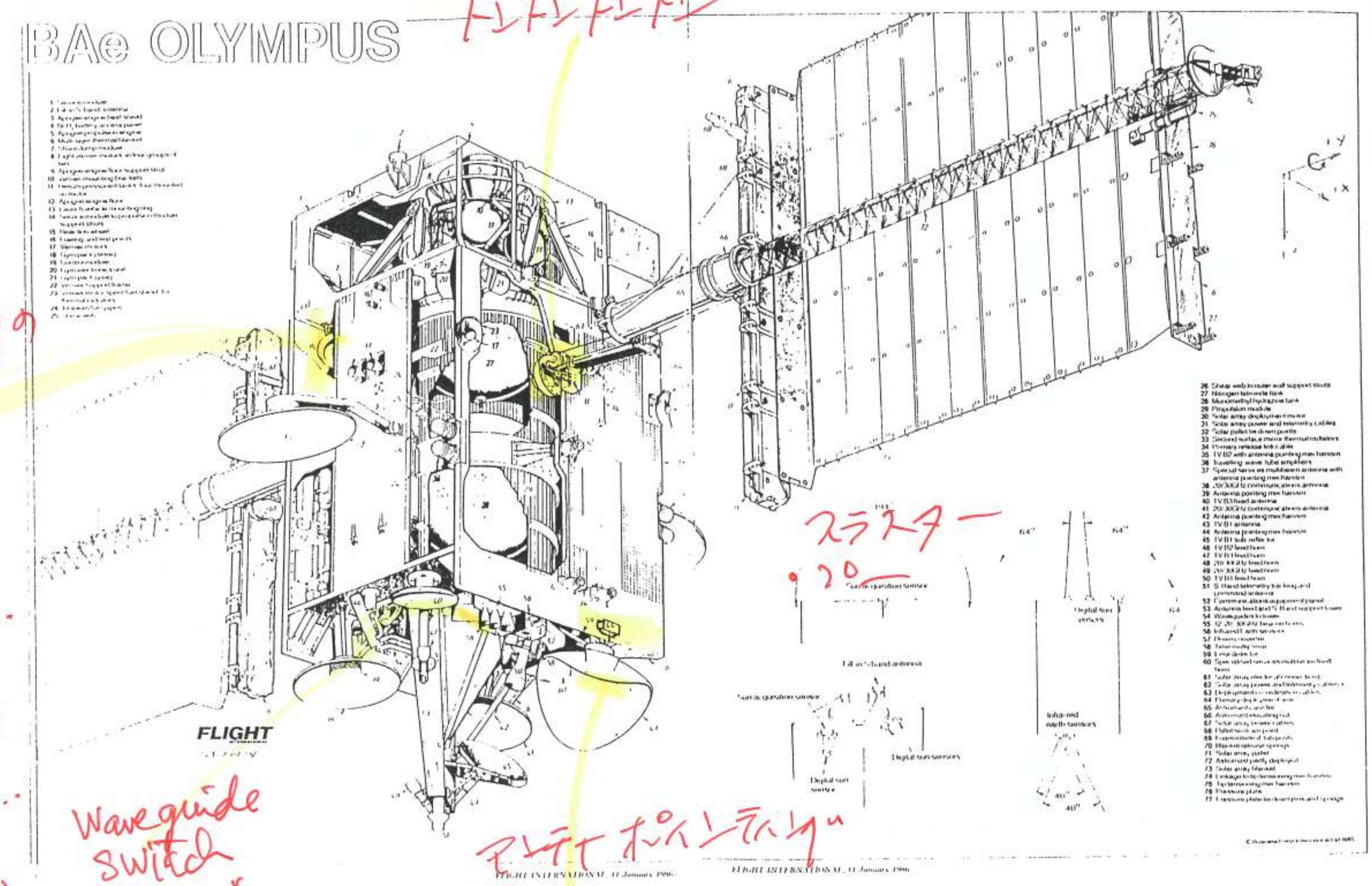
Effect of Microaccelerations on an Optical Space Communication System

ゴー…
トントントントン



古い工場のモーターの音.

スラスター
ゴー

ドドドド…
機関銃.

ドゥドゥドゥ…
ドゥドゥ…
(高い声)

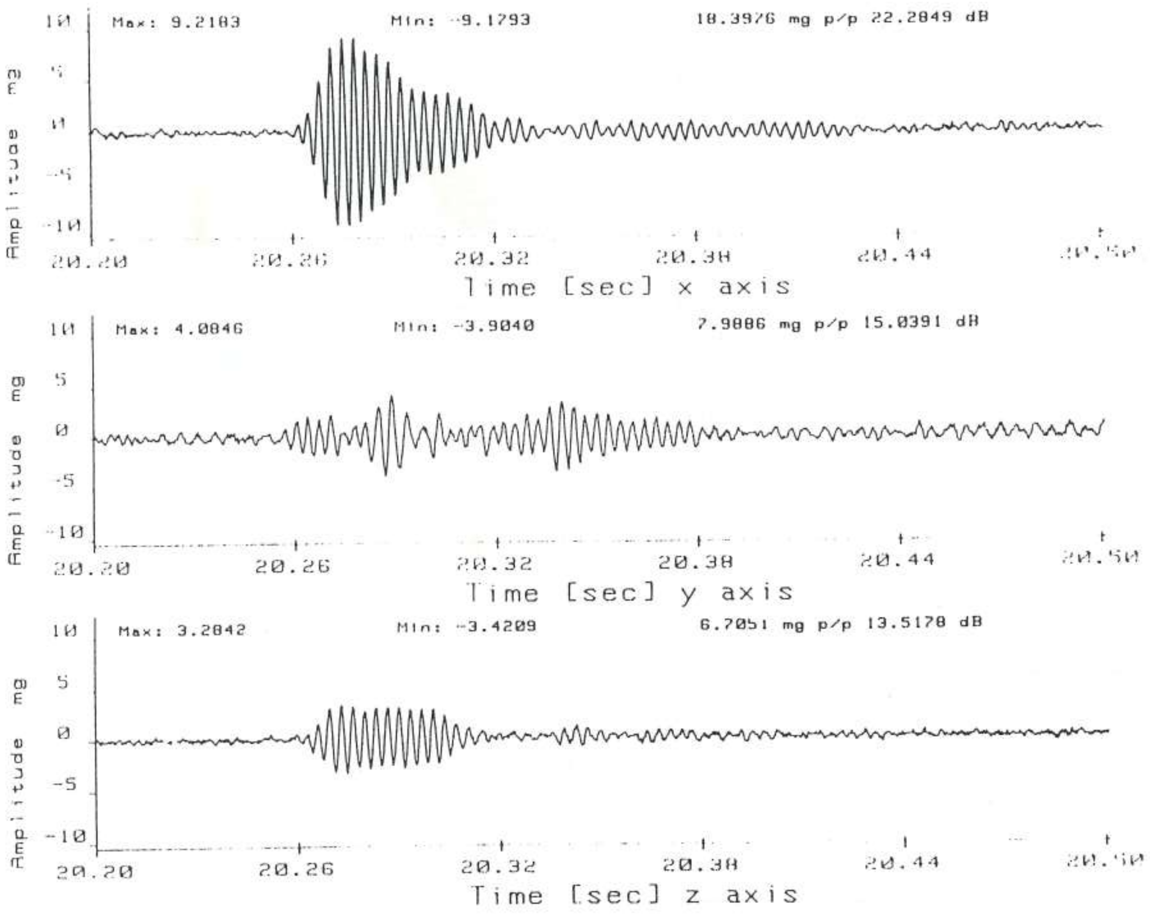
Waveguide switch
"ワンワン"

スラスター
20

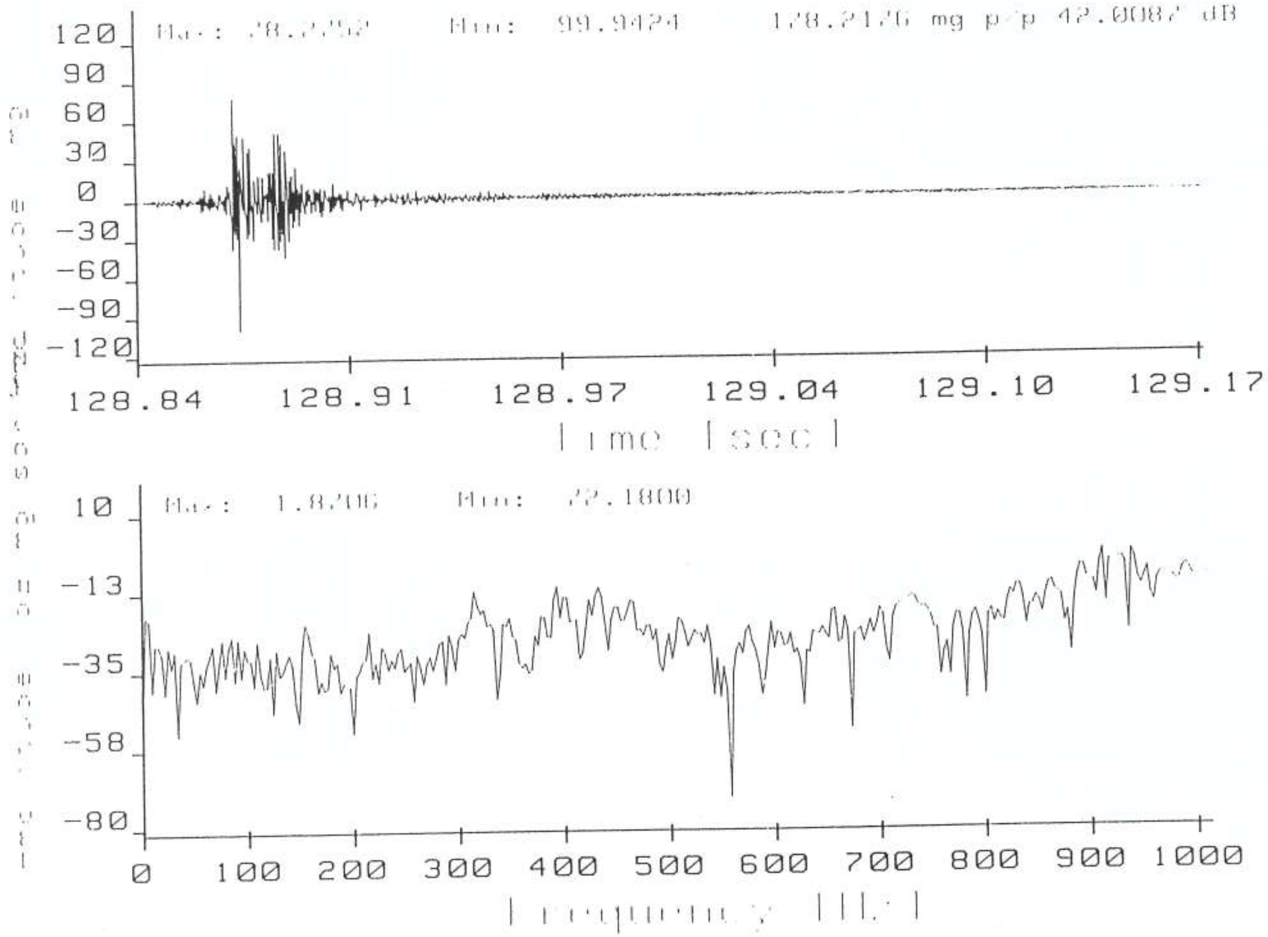
アンテナポインティング
ゴー…
ブーン, ブーン

マイクロステップモード.

Solar Array Drive Mechanism



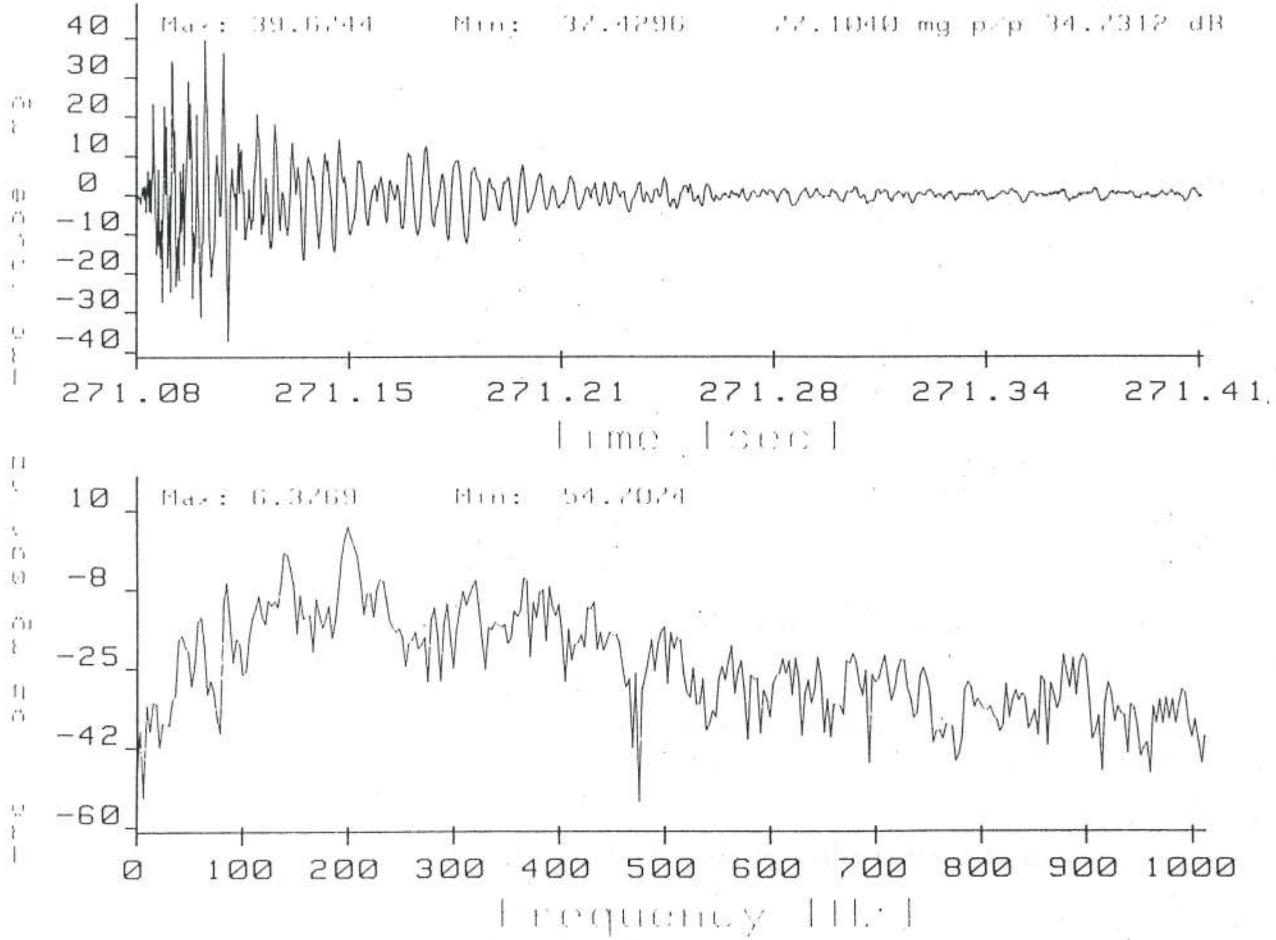
Operation of a Waveguide Switch



Effect of Microaccelerations on an Optical Space Communication System

esa

Short Thruster Firing



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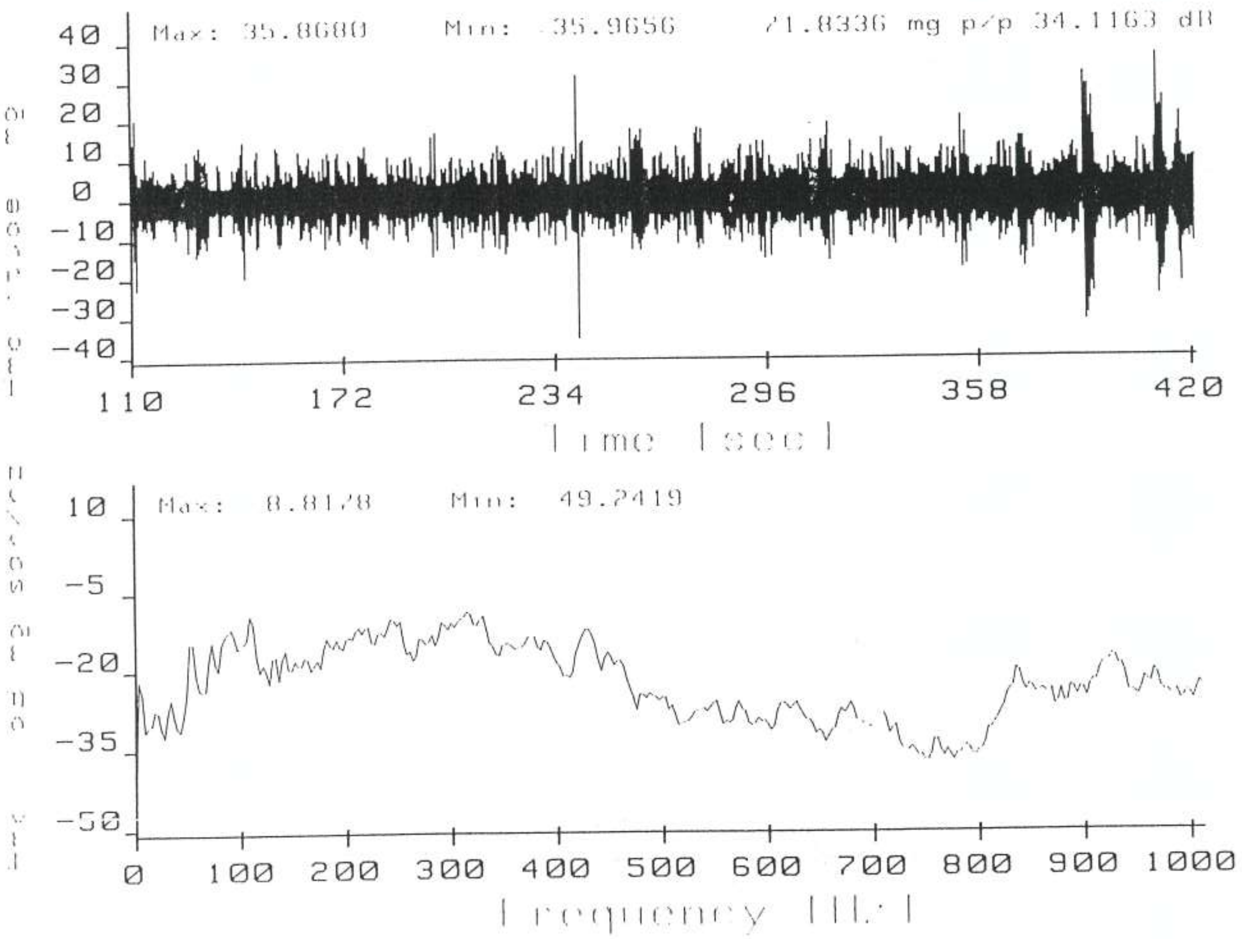
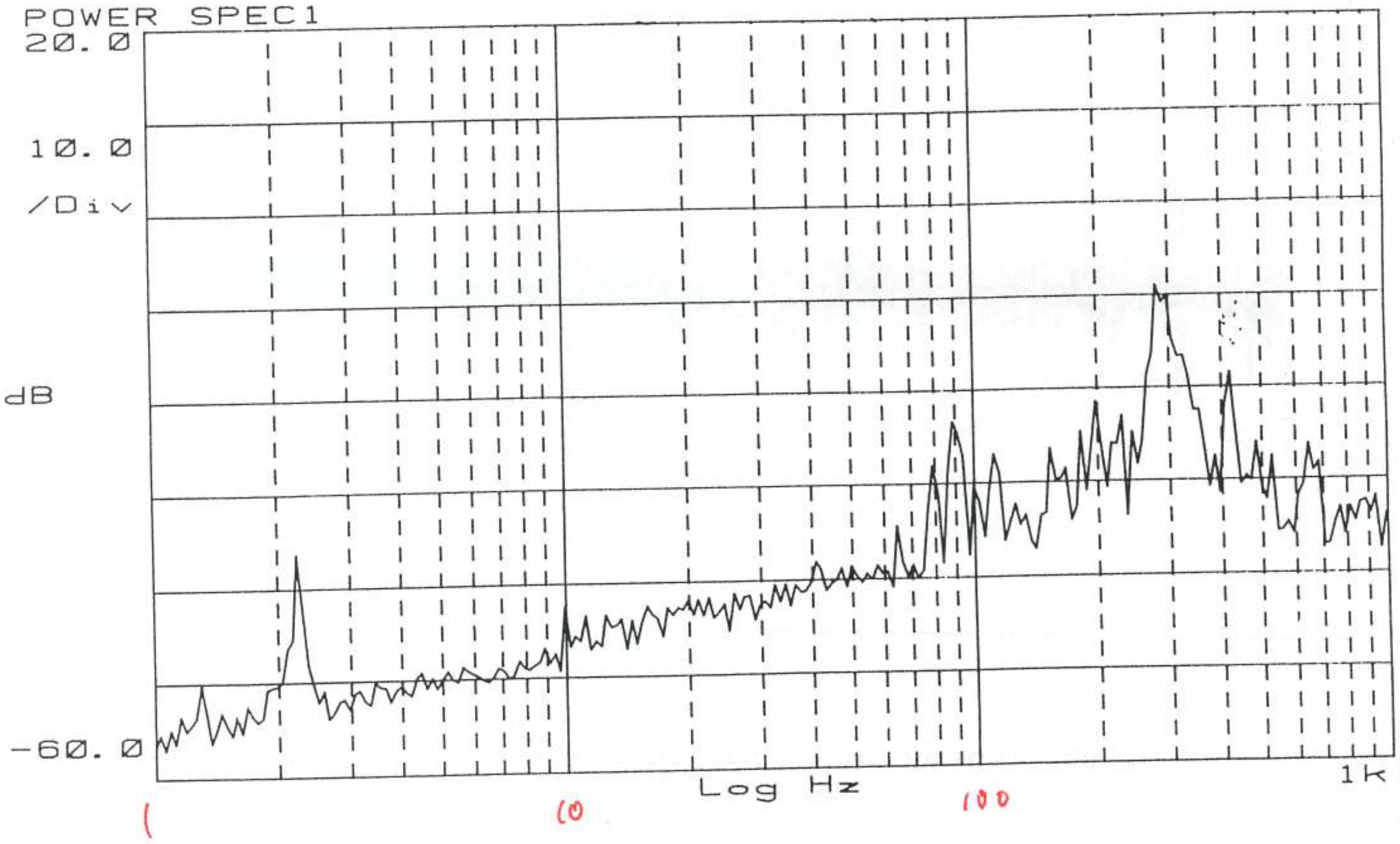
Long Thruster Burn



Effect of Microaccelerations on an Optical Space Communication System

esa

Accelerations observed during ~~2~~ 20 minutes



20dB/decade

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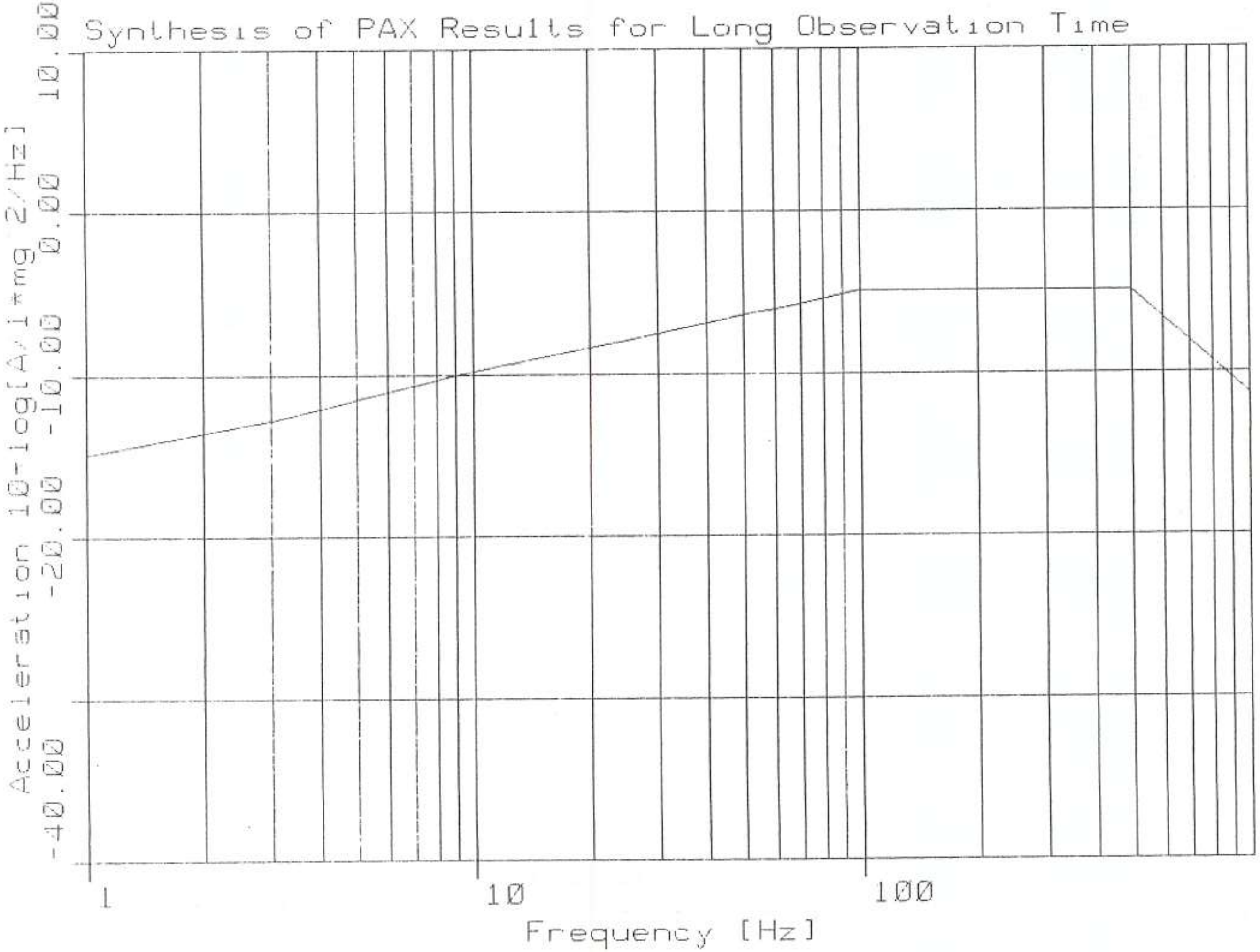
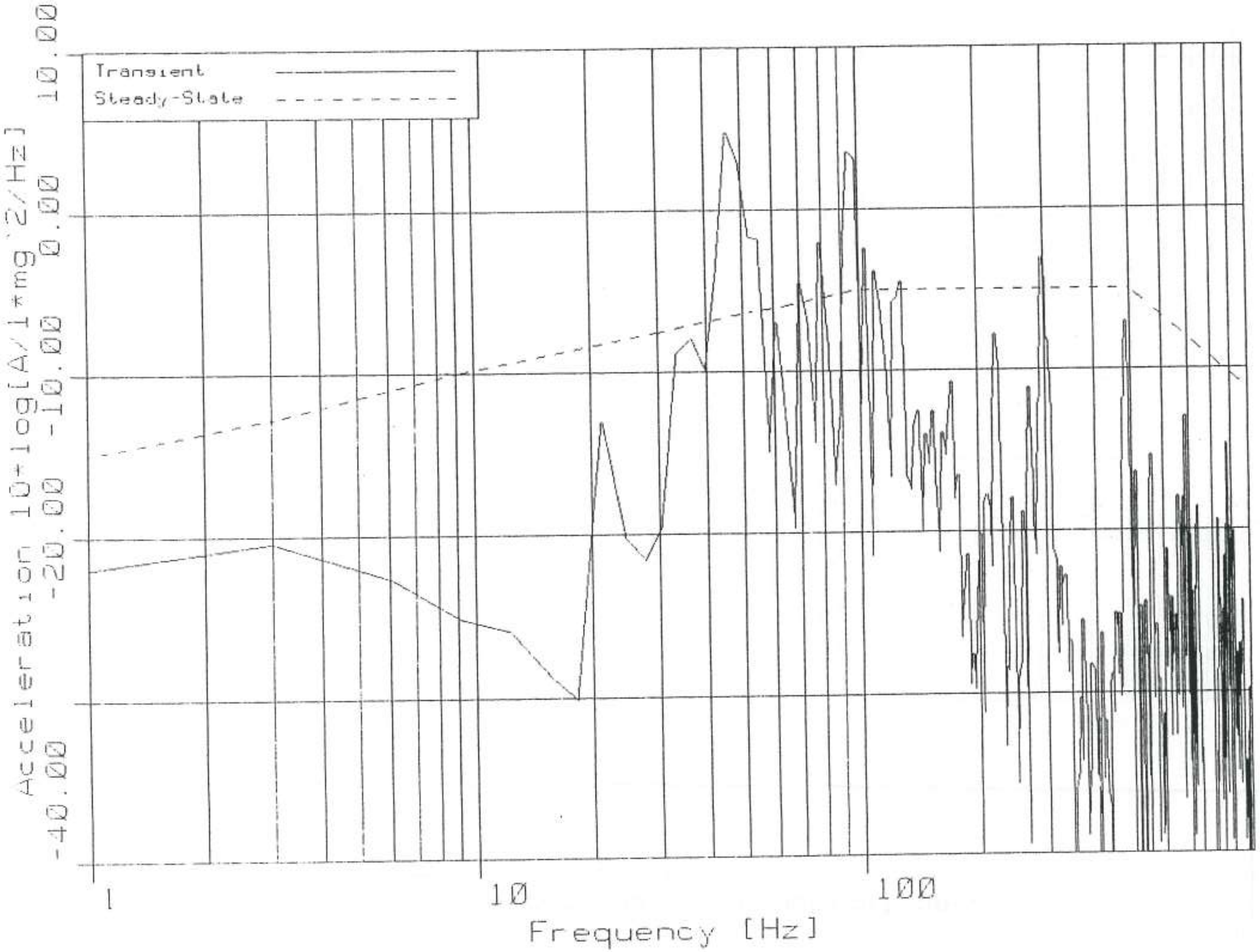
Effect of Microaccelerations on an Optical Space Communication System

Synthesis of PAX Results for Long Observation Time



Effect of Microaccelerations on an Optical Space Communication System



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Effect of Microaccelerations on an Optical Space Communication System

* INFLUENCE OF POINTING ERRORS ON LINK QUALITY

* MICROVIBRATIONS FROM HOST SPACECRAFT

* PAX

*** TRANSFER OF MICROVIBRATIONS BY STRUCTURE**

* OPTIMIZATION OF CONTROL LOOP

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Effect of Microaccelerations on an Optical Space Communication System

Transfer of Acceleration A to Rotataion

$$M(f)_{xy} := \frac{\theta(f)_{xy}}{A(f)_{yz}}$$

For a rigid body we obtain

$$S\theta(f)_{xy} := \frac{1}{\omega^{4} \cdot l^{2}} \cdot SA(f)_{yz}$$

and for a real body

$$S\theta(f)_{xy} := M(f)_{xy}^{2} \cdot SA(f)_{yz}$$

for example from a Finite Element **M**odel or Measurement

A key parameter is the length l.

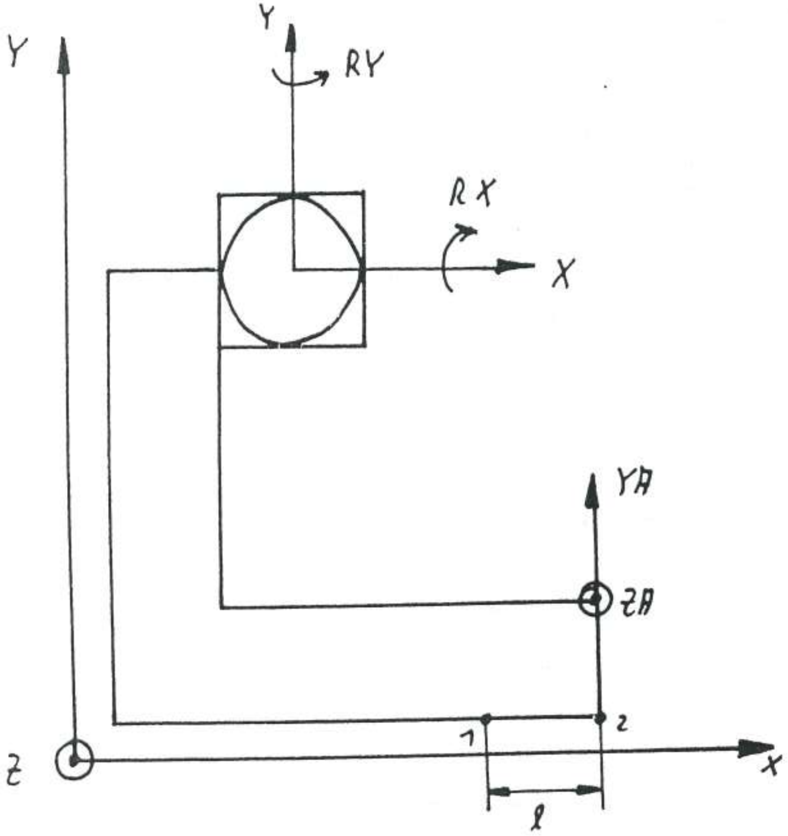
If the rigid body approach shall be used
the length l shall be replaced by the effective length

$$l_{eff} := \frac{0.01462}{\sqrt{\int_{fl}^{fu} M(f)^{2}\, df}} \cdot \sqrt{\frac{1}{fl^{3}} - \frac{1}{fu^{3}}}$$

which is derived from equal Integral over the frequency
range for the rigid body and the FEM

Effect of Microaccelerations on an Optical Space Communication System

Example of a Mechanical Structure



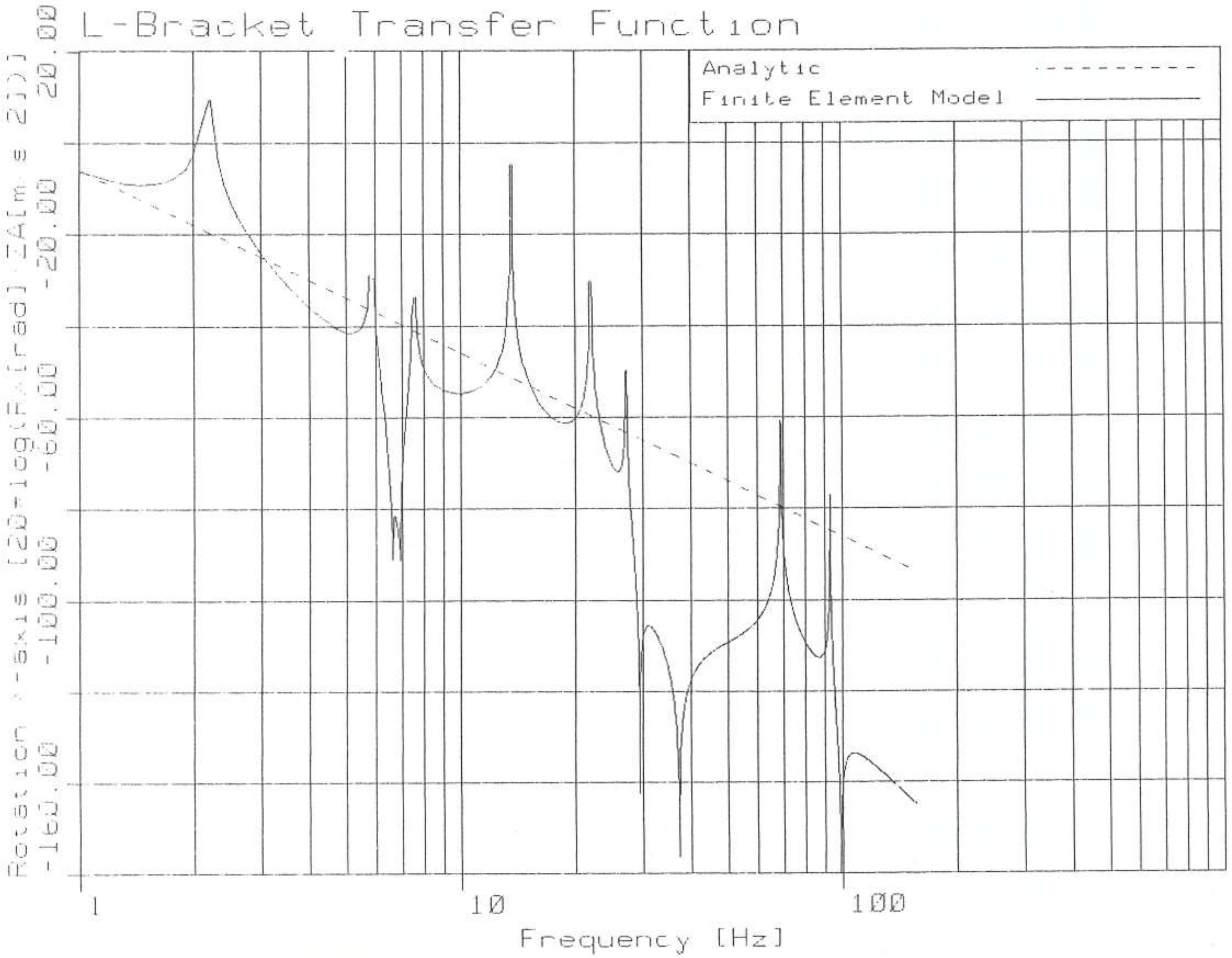
Geometry of L-Bracket

Length	350 mm
Width	200 mm
Height	400 mm
Thickness	20 mm
l	50 mm
Mass Density	1.7 Kg/cm^3
Young's Modulus of elasticity	25 000 kp/mm^2
Poisson' ratio	0.35
Mass of Telescope	40 Kg
Inertia of Telescope	$I_x = I_y = I_z = 4\ Kg/m^2$

1 fixed

2 Acceleration applied

Effect of Microaccelerations on an Optical Space Communication System



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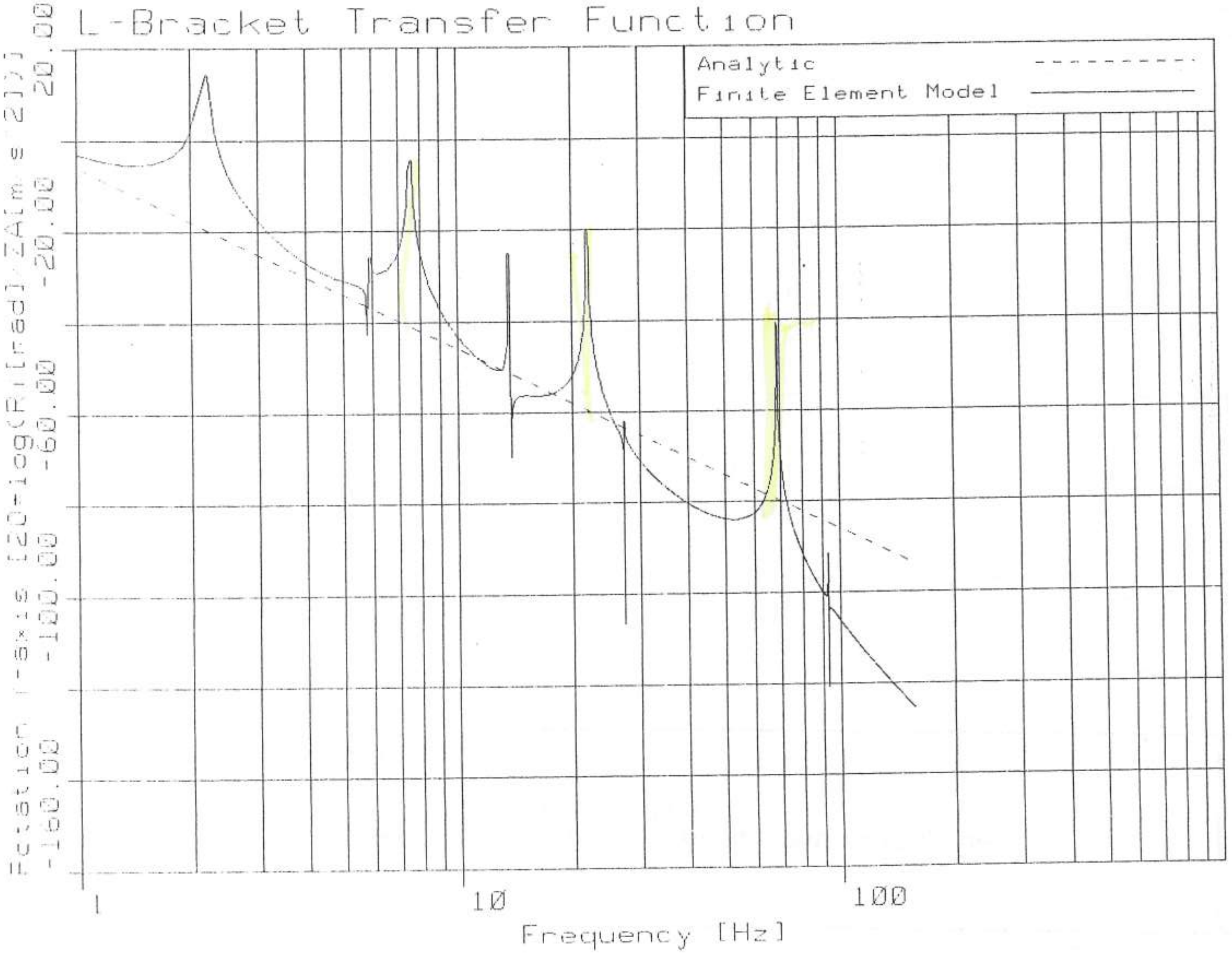
Effect of Microaccelerations on an Optical Space Communication System


L-Bracket Transfer Function

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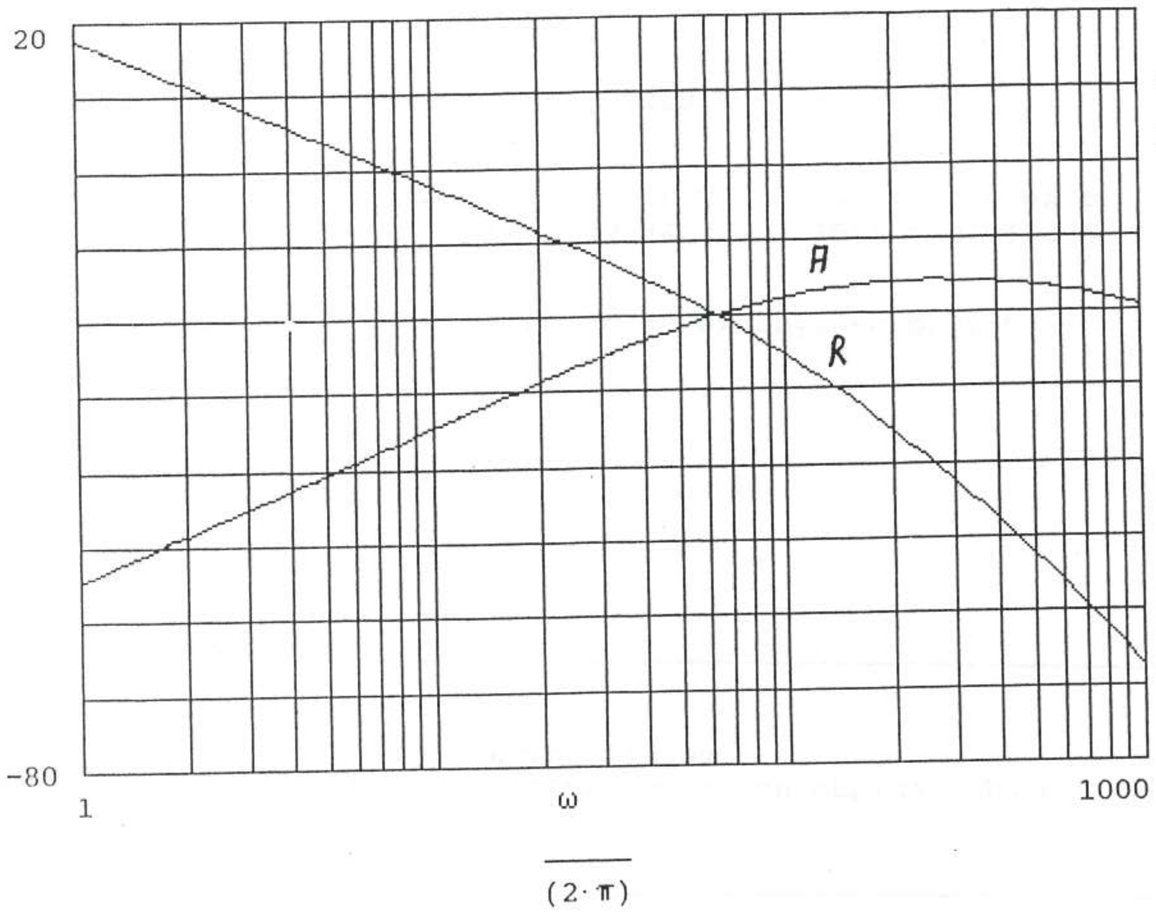
For the L-bracket considered as an example we obtain

Rotation about x by Acceleration at Z	leff = 0.0119 m
Rotation about y by Acceleration at Z	leff = 0.0069 m

and is less than the original length l = 0.05 m

Effect of Microaccelerations on an Optical Space Communication System

Rotation Spectra derived from Acceleration Spectra



A = 20*log(a/(1 mg/sqrt(Hz)))

R = 20*log(R/(1 µrad/sqrt(Hz)))

l = 0.25 m

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Effect of Microaccelerations on an Optical Space Communication System

- INFLUENCE OF POINTING ERRORS ON LINK QUALITY
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- **OPTIMIZATION OF CONTROL LOOP**

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Tracking Control Loop

Consists of

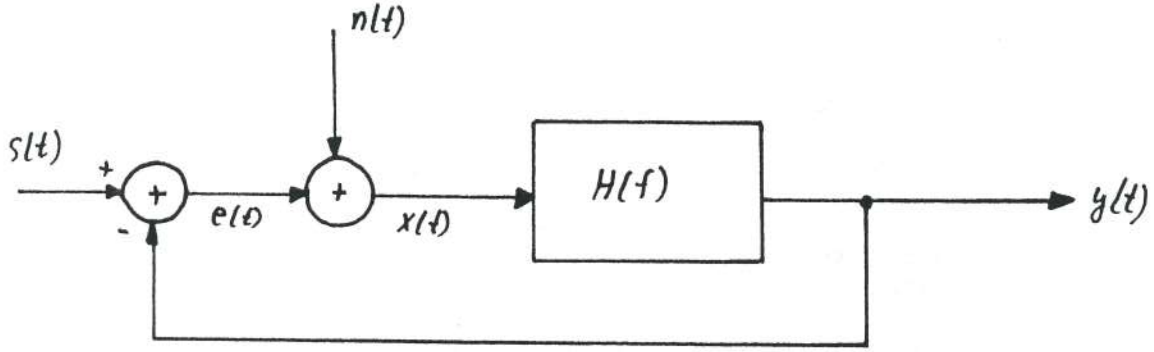
* Detector (Quadrant Detector, CCD)
* Controler
* Pointing Mechanism

Error Sources

* Noise of the sensor
  is generated inside the control loop

* Microvibration induced pointing angles
  is genereated outside the control loop

Tracking Loop



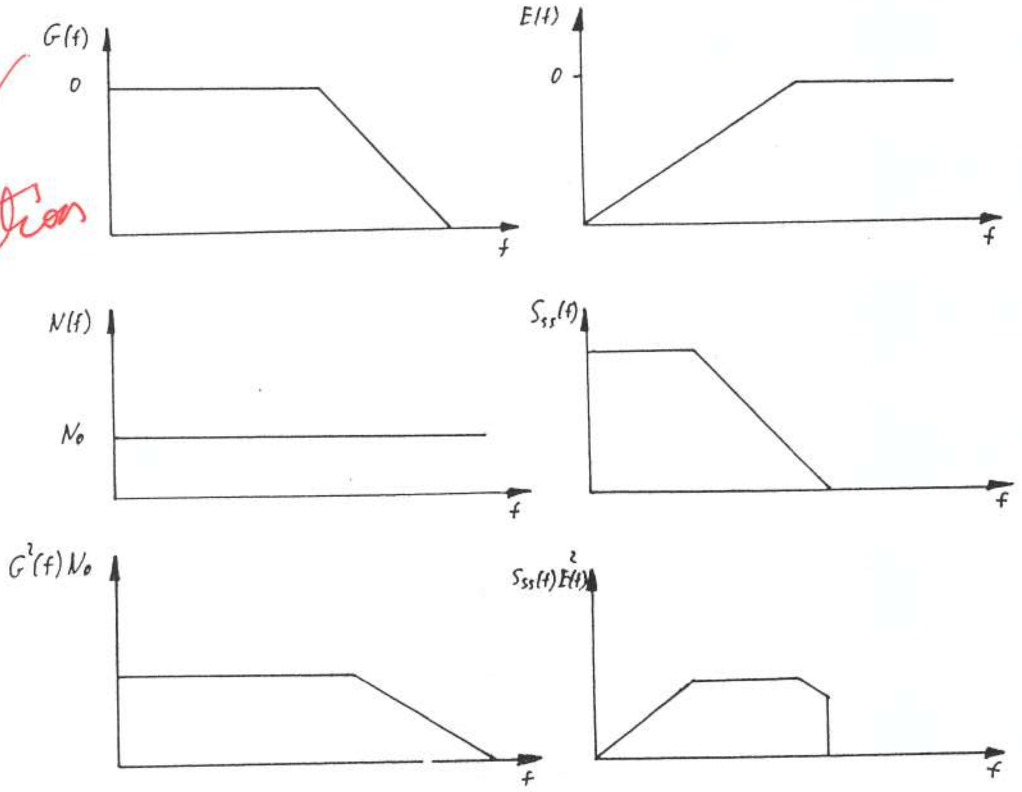
$$G(f) = \frac{H(f)}{1 + H(f)}$$

$$E(f) = 1 - G(f)$$

Spectra of Sensor Noise and Pointing Angles

Noise of the Sensor

Transfer function



Microvibrations

error spectral density

Optimiztion of Tracking Control Loop

Minimization of rms-tracking error

$$\sigma^2 := e(t)^2$$

$$e(t)^2 := E(s(t) - y(t))^2$$

is achieved by a Wiener-Filter

$$Go(\omega) := 1 - \frac{\sqrt{\frac{No}{2}}}{\Phi(\omega)}$$

with

$$S(\omega)_s := S(\omega)_{ss} + \frac{No}{2} \qquad S(z)_s := S(z)_{ss} + N(z)$$

$$S(z)_s := \Phi(z) \cdot \Phi(z)^x$$

Effect of Microaccelerations on an Optical Space Communication System

$$S(\omega) := \frac{A}{\omega^2 + a^2}$$

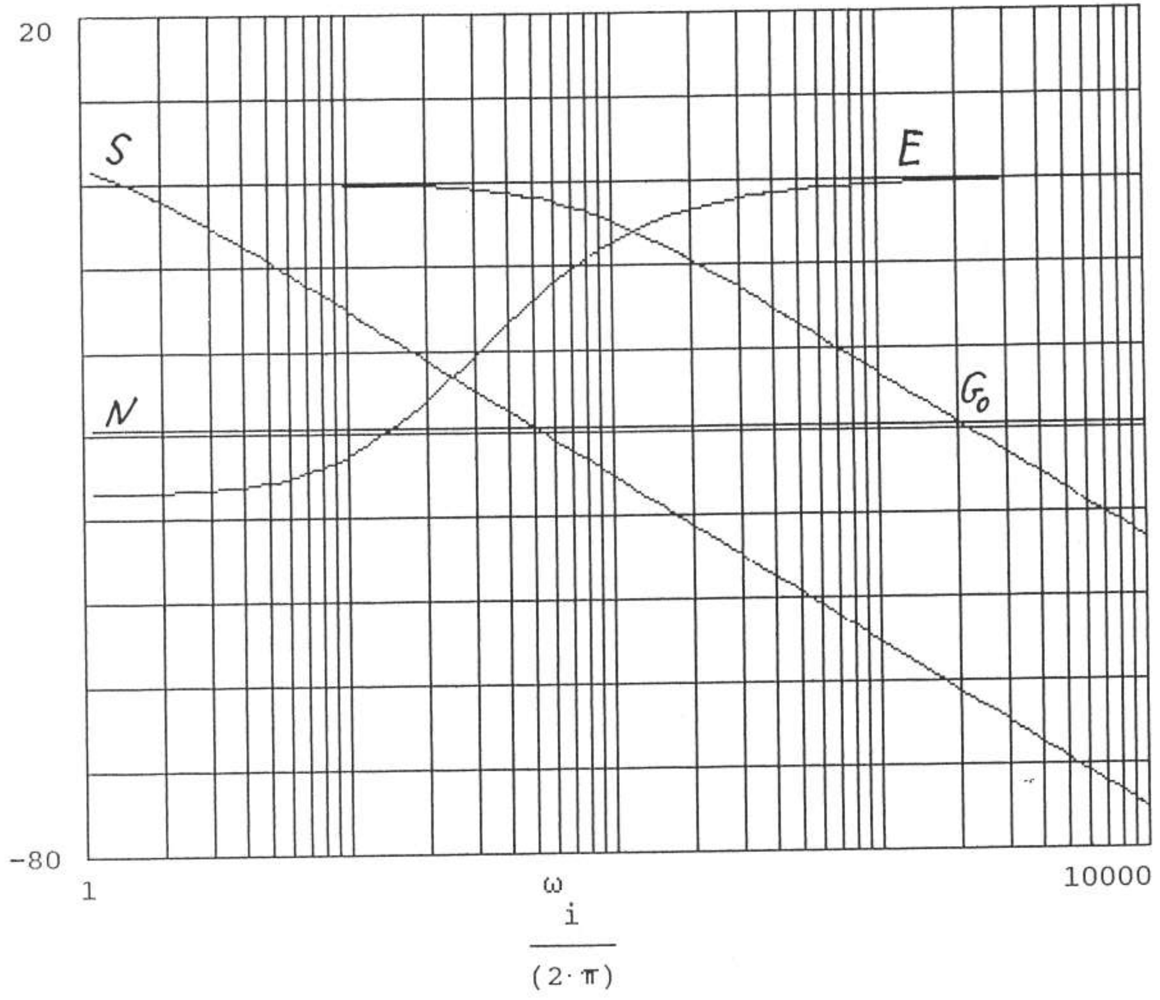
$$Go(\omega) := \frac{b - a}{j \cdot \omega + b}$$

$$b := \sqrt{a^2 + 2 \cdot \frac{A}{N}}$$

$$a := 2 \cdot \pi \cdot 1 \cdot \mathrm{Hz}$$

$$A := a^2 \cdot 3 \cdot 10^{-6} \cdot \mathrm{rad}$$

$$N := 0.0012 \cdot 10^{-6} \cdot \mathrm{rad}$$



$\sigma_{in} = 3.85\ \mu\mathrm{rad}$

$\sigma_{out} = 1.1\ \mu\mathrm{rad}$

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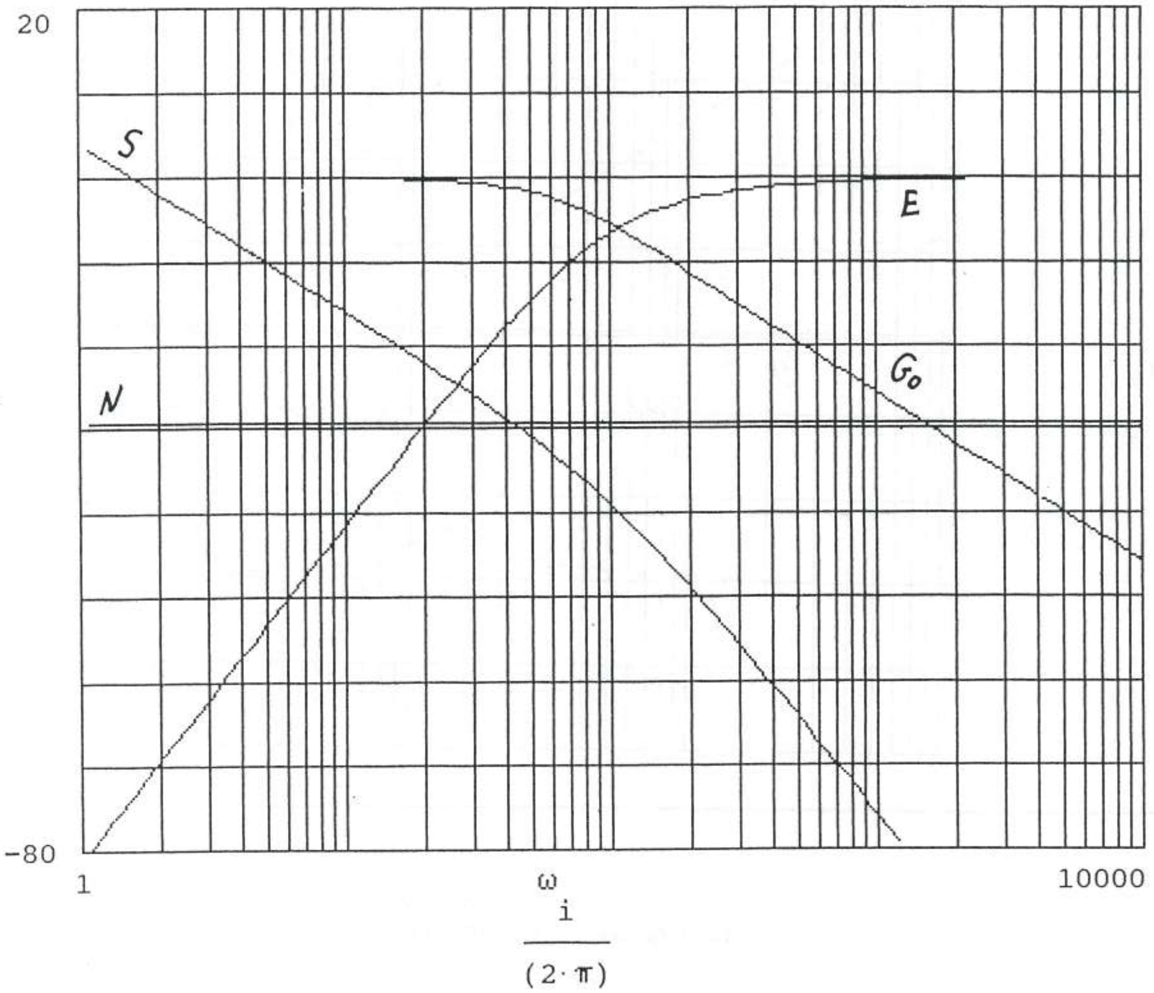
Effect of Microaccelerations on an Optical Space Communication System

$$S(\omega) := \frac{A}{\omega^2 + a^2} \cdot \frac{1}{\omega^2}$$

$$Go(\omega) := \frac{c + \left[\sqrt{a^2 + 2\cdot c} - a\right]\cdot j\cdot\omega}{c + \left[\sqrt{a^2 + 2\cdot c\cdot j\cdot\omega} - \omega^2\right]}$$

$$c := \sqrt{2\cdot\frac{A}{N}}$$

$$a := 2\cdot\pi\cdot 100\cdot Hz$$



$\sigma_{in} = 3.96\ \mu rad$

$\sigma_{out} = 0.98\ \mu rad$

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CONCLUSION

- * The in-orbit measurements of microvibrations have shown that Transients are the most disturbing sources
- * The steady-state microacceleration spectra shows a reverberate behaviour above 100 Hz
- * A control loop transfer function can be derived which minimzes the rms-error caused by sensor noise and the steady-state microvibrations induced by the spacecraft
- * The transformation of acceleration to rotation predictions by Finite Element Models needs to be verfied by measurements

4-3

Research on OSC and optical space technologies at ISAS

Tadashi Takano

Institute of Space and
Astronautical Science

IWOSC '90
December 6 and 7, 1990, ATR, Kyoto

Research on OSC and Optical Space Technologies at ISAS

ABSTRACT

Optical technologies have been studied to realize fiber communications systems and mass memory systems based on the development of lasers and opto-electronic components. The trend is still going on to seek for higher data transmission rate and larger memory capacity.

Turning eyes to space communities, there have been few achievements to utilize modern optical technologies in space, though inter-satellite links using lasers were studied from 1970s. The reasons are that space systems most value reliability and efficiency per weight. Systems and devices should be proved on the ground.

Another difficulty of optical technologies is tropospheric effects to propagating light beams. Therefore, light beam technologies are most suitable to be used in free space. As space activities are expanded farther and in larger scale, and reliability of opto-electronic components is highly improved, optical technologies will be used for many missions in future.

Institute of Space and Astronautical Science, Japan, have put several optical technologies into actual use, such as a star tracker, a star scanner, fiber harness or a fiber optical gyro. The basic research of ISL and a laser radar has been also started. In this presentation, I would like to briefly survey the results of these applications and present status of research works.

The link analysis of ISL and a laser radar for two missions are given to show the possibility of actual use. Then, a novel precise angle gauge is described. The phase difference between two extracted rays from incoming laser light is compensated by a phase modulation, The angle of the incident light is measured by the modulation voltage, the resolution being up to 10-7 rad.

Instruments using beams tend to suffer from performance degradation due to diffraction phenomena. The method to suppress Fresnel diffraction by spatial filters is studied, theoretically and experimentally.

BIOGRAPHY

Tadashi Takano

Dr. Takano was born in Tsukuba, Japan on February 19, 1945. He received the B.S., M.S. and Ph.D. degrees in electronics engineering from the University of Tokyo, in 1967, 1969 and 1972, respectively.

He joined the Electrical Communication Laboratories of Nippon Telegraph and Telephone Public Corporation, in 1972. where he worked with research and development on primary radiators, the antennas for 20 GHz band terrestrial relay systems, the earth station and ship terminal antennas for the Japanese domestic satellite communications system and antenna application problems related to communications systems.

He moved to the Institute of Space and Astronautical Science, Japan in 1984, where he is currently an associate professor. His research interests include antenna engineering, radio wave applications and telecommunication engineering.

He received the Yonezawa Award for the experimental and analytical study on cross polarization characteristics of aperture antennas, from the Institute of Electronics and Communication Engineers of Japan in 1975.

Dr. Takano is a member of the Institute of Electronics, Information and Communication Engineers, the Japan Society of Information and Communication Research, and IEEE.

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IWOSC '90

Research on OSC and Optical Space Technologies at ISAS

December 7, 1990

Tadashi Takano

Institute of Space and Astronautical Science

OUTLINE

1. Introduction

2. Possibility of Inter-Satellite Link Communications

3. Possibility of Laser Radars

4. Practical Use of Optical Technologies
   - 4.1 Fiber Harness in Satellites
   - 4.2 Star Tracker and Star Scanner

5. Investigations of Basic Techniques
   - 5.1 Quadrant Detector Radar
   - 5.2 Angular Measurement Using Phase Modulation
   - 5.3 Beam shaping and Fresnel Diffraction Suppression

ISL APPLICATIONS IN ISAS ACTIVITIES

1. Features of Inter-Satellite Link
   (1) Large capacity
   (2) Light weight
   (3) Attitude stability requirement to utilize a narrow beam

2. Possible application fields
   (1) From a deep space explorer to a data relay satellite on the geo-synchronous orbit
   (2) Between tethered satellites

BUDGET OF THE TETHERED SATELLITES RADIO LINK

ITEM	VALUE	NOTE
LASER OUTPUT	200 mW	GaAlAs LD, 0.85μm
TRANSMIT ANTENNA GAIN	81 dB	1cmφ, η=0.1, FEED
FREE SPACE LOSS	-243 dB	100km
RECEIVE ANTENNA GAIN	101 dB	10cφ, η=0.1, FEED
RECEIVE POWER LEVEL	-38 dBm	
MODULATION LOSS	-9 dB	DIRECT DETECTION
MISCELLANEOUS LOSS	-3 dB	CCT IMPERFECT., ETC.
SIGNAL POWER LEVEL	-50 dBm	
BIT RATE	80 dBHz	100Mbps
POWER PER BIT	-130 dBm/Hz	
RECEIVER NOISE	-152 dBm/Hz	2hf/ξ, ξ=0.7, Si
Eb/NO	22 dB	
REQUIRED Eb/NO	10 dB	BPSK, BER<10E-5
MARGIN	12 dB	

optical link is promissing

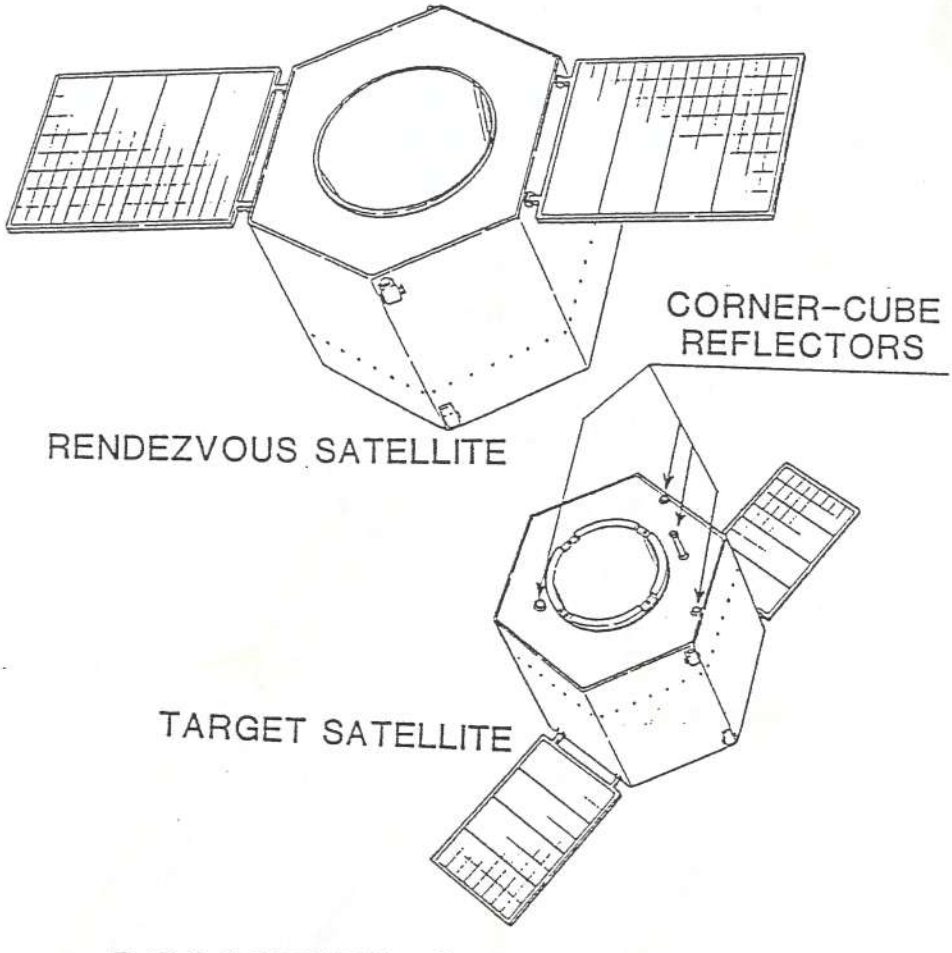
BUDGET OF THE TETHERED SATELLITES FIBER LINK

ITEM	VALUE	NOTE
LASER OUTPUT	10 mW	InGaAsP LD, 1.3 μm
TRANSMIT MATCHING LOSS	1 dB	CONNECTOR, ETC.
FIBER LOSS	-80 dB	100Km, SM FIBER 0.2 dB/km at 1.5 μm.
RECEIVE MATCHING LOSS	1 dB	CONNECTOR, ETC.
RECEIVE POWER LEVEL	-72 dBm	
MODULATION LOSS	-9 dB	DIRECT DETECTION
MISCELLANEOUS LOSS	-3 dB	CCT IMPERFECT., ETC.
SIGNAL POWER LEVEL	-84 dBm	
BIT RATE	57 dBHz	500Kbps
POWER PER BIT	-141 dBm/Hz	
RECEIVER NOISE	-154 dBm/Hz	$2hf/\xi$, $\xi=0.7$, Ge
Eb/N0	13 dB	
REQUIRED Eb/N0	10 dB	BPSK, BER<10E-5
MARGIN	3 dB	

LASER RADAR APPLICATIONS IN ISAS ACTIVITIES

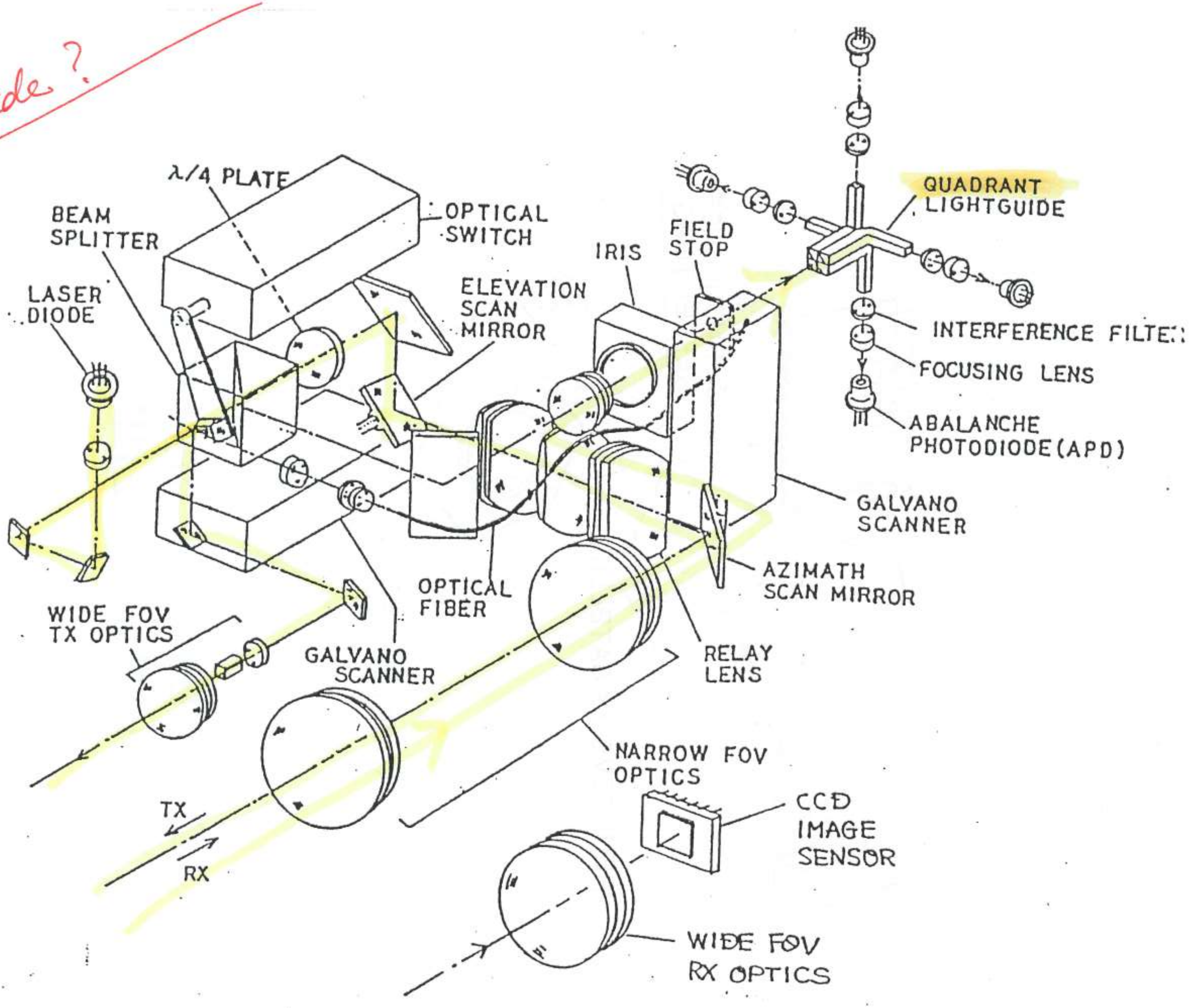
1. Features of Laser Radar
   (1) Light weight
   (2) Measurement precision

2. Possible Application Fields
   (1) Rendezvous with another spacecraft or a celestial body
   (2) Tethered satellites
   (3) Lander on a celestial body

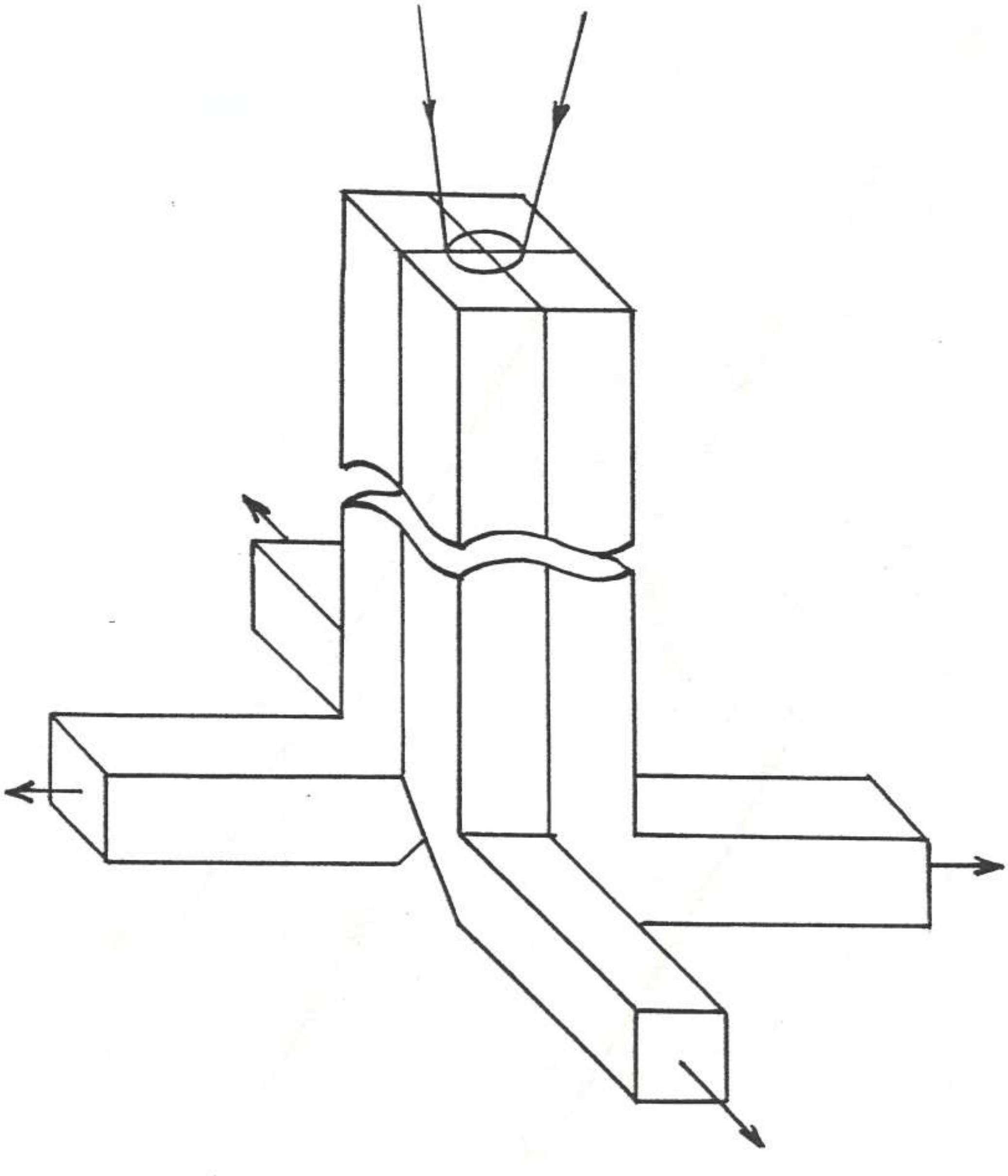


CONCEPT OF RENDEZVOUS DOCKING EXPERIMENT best location of optical light guide ?

pupil point



Optical System of Laser Radar



LIGHT GUIDE FOR QUADRANT DETECTOR

phase comparator

SCANNING LASER RADAR OPERATION-MODE

	RANGE	MODE	SUB-MODE	LASER BEAM WIDTH		SENSOR BEAM WIDTH		RESOLUTION	SCANNING MODE	SAMPLING PERIOD	TONE FREQUENCY
				0.12°	30°	CCD 30°	QD 0.12°				
NEAR FIELD	1m ~200m	TRACKING	TRACKING	—	○	○	—	± 0.08mrad	—	1/30sec	—
			RANGING	○	—	—	○	± 5cm	SLAVE TO CCD	0.1sec	15MHz / 150KHz
FAR FIELD	200m ~20km	ACQUISITION		○	—	—	○	2mrad	5°x5° scan 30°x30° slow-scan	~7sec ~250sec	15MHz / 150KHz / 7.5KHz
		TRACKING	TRACKING	○	—	—	○	± 0.4mrad	SLAVE TO QD	0.1sec	
			RANGING	○	—	—	○	± 5cm	〃	0.1sec	

REQUIREMENTS OF A LASER RADAR CHARACTERISTICS

1. Tethered Satellite

(1) Cooperative radar: Target carries a reflector.
(2) Measurement distance: 10 m - 100 km.
(3) Measured value:
  a) the angle change of the child satellite seen from the parent satellite in the time scale of around 10 minutes,
  b) velocity along the view line: around 1 m/sec.

2. Lunar Lander

(1) Beginning of descend at 20-100 km altitude: Watching the total geographical features.
(2) Fine control descend from 100 km altitude: discriminating the local geographical features,
  accuracy: 0.1 m
  view angle: 10 deg.

S/N ANALYSIS OF A LASER RADAR

ITME	VALUE	NOTE
LASER OUTPUT	5MW/PU	YAG 1.5μm(PUB 20ns)
LASER BEAM BROADENING	50cm/2km	
RECEIVE POWER LEVEL	-36dBw/PU	RECEIVE LENS 40mmφ
MISCELLANEEOUS LOSS	-3dB	
SIGNAL POWER LEVEL	-39dBw/PU	
NEP OF PD	-140dBw/Hz	Si PD
RECEIVER NOISE	-57dBw/PU	PD, AM, ETC(f=100MHz)
Eb/N0	18dB	
REQUIRED Eb/N0	15dB	FOR $P_N 10^{-10}$, P_D90%
MARGIN	3dB	

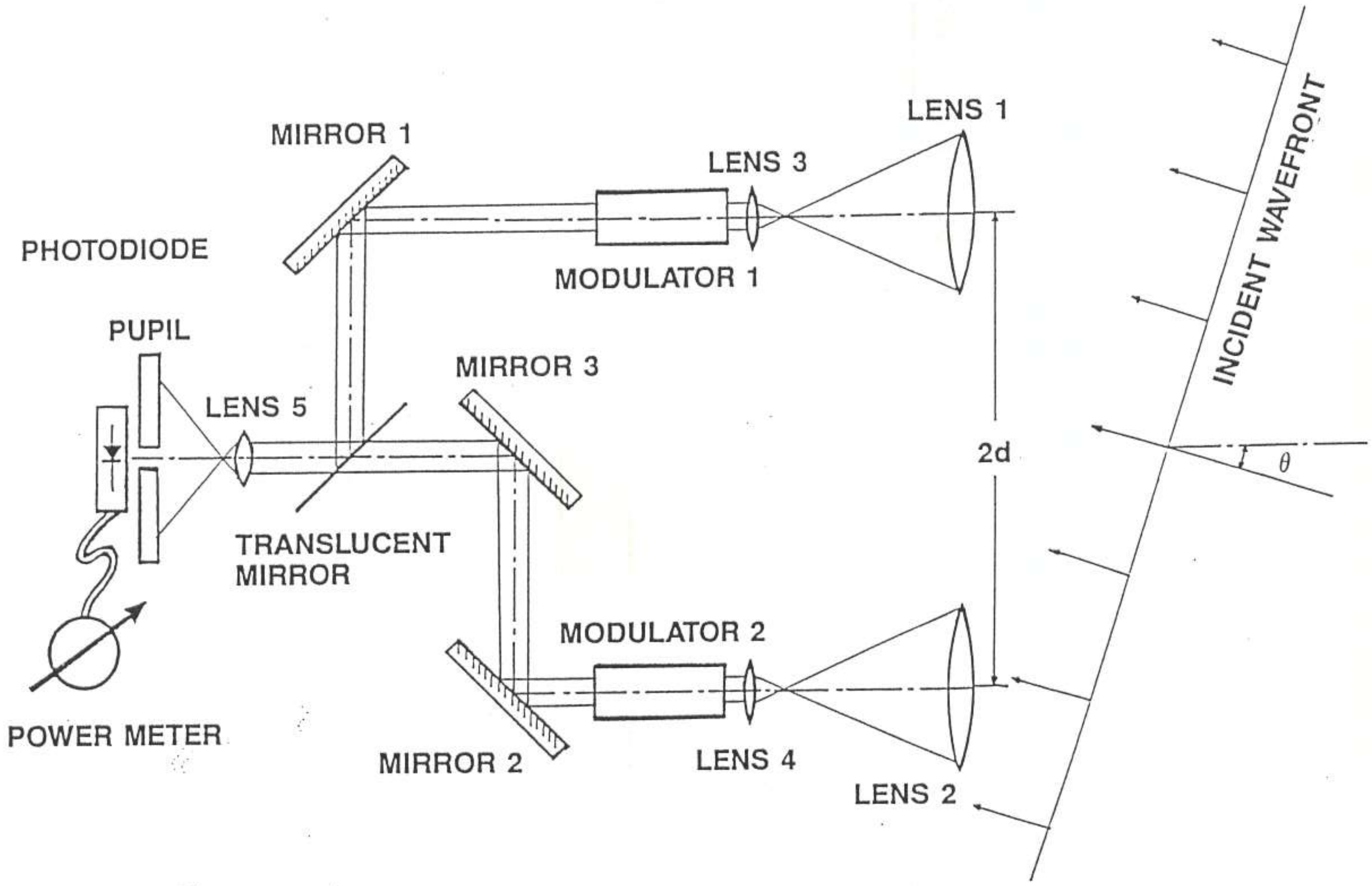


Figure Basic Configuration of the Angle Gauge

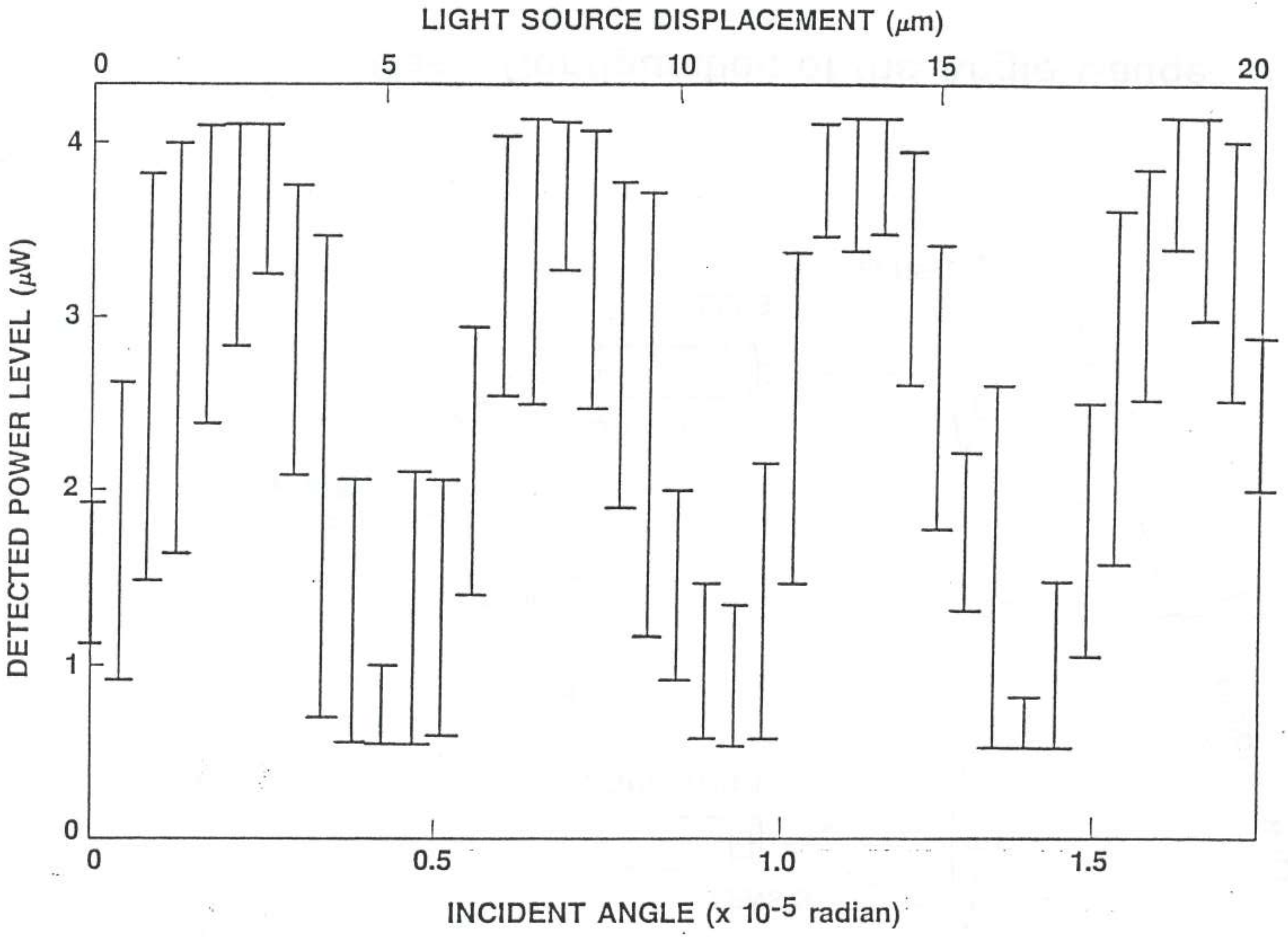


Figure Interference Characteristics Versus Incident Angle (Narrow Angle Range)

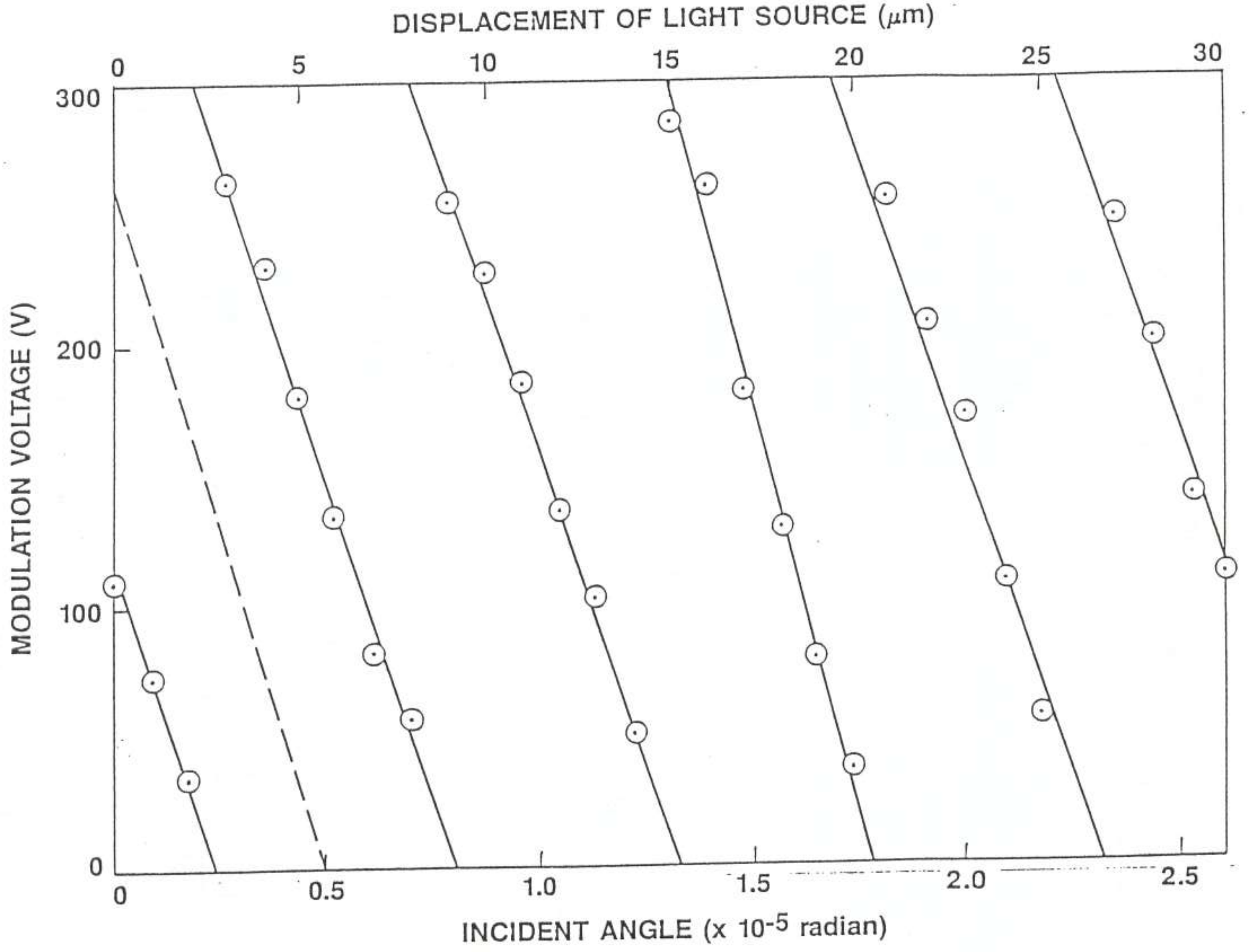
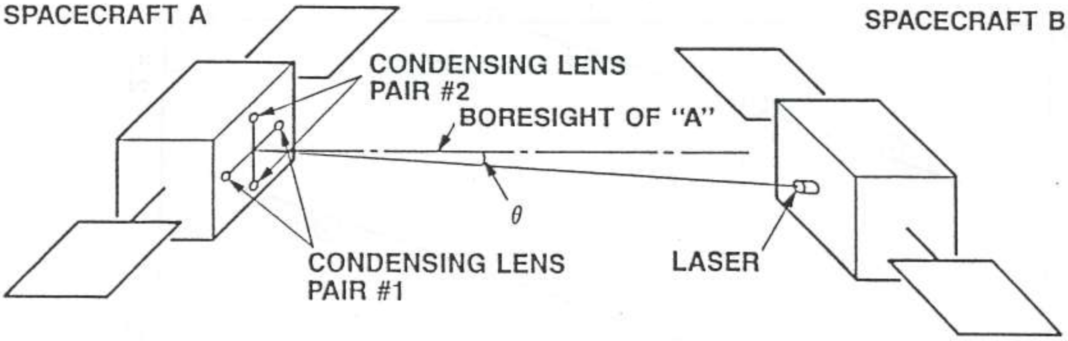
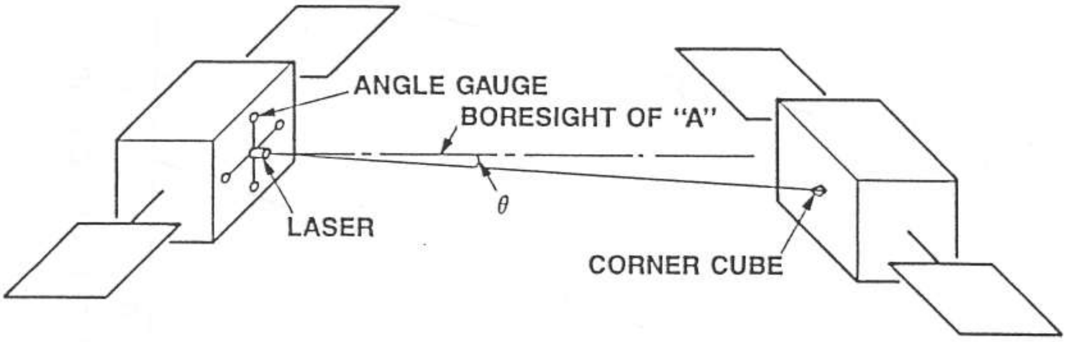


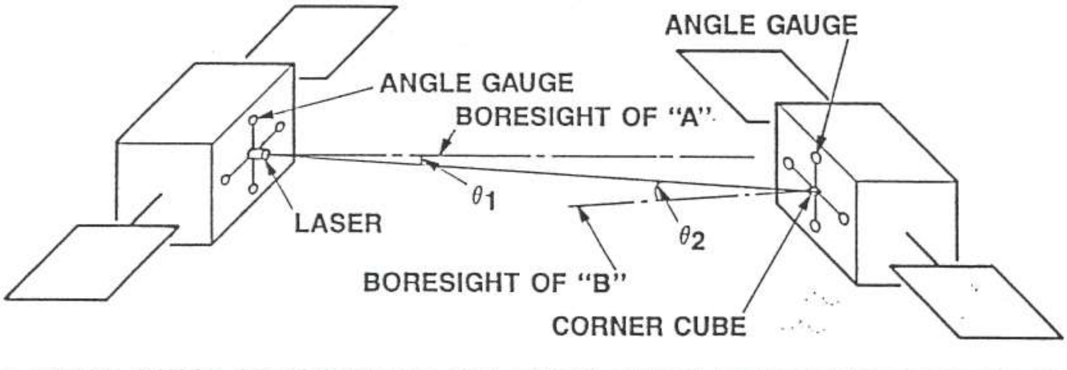
Figure Angle Measurement by Modulation Voltage



(a) ANGLE GAUGE ON "A", LASER ON "B"



(b) ANGLE GAUGE AND LASER ON "A", CORNER CUBE ON "B"



(c) ANGLE GAUGE AND LASER ON "A", ANGLE GAUGE AND CORNER CUBE ON "B"

Figure Application to Spacecraft Tracking and Attitude Control

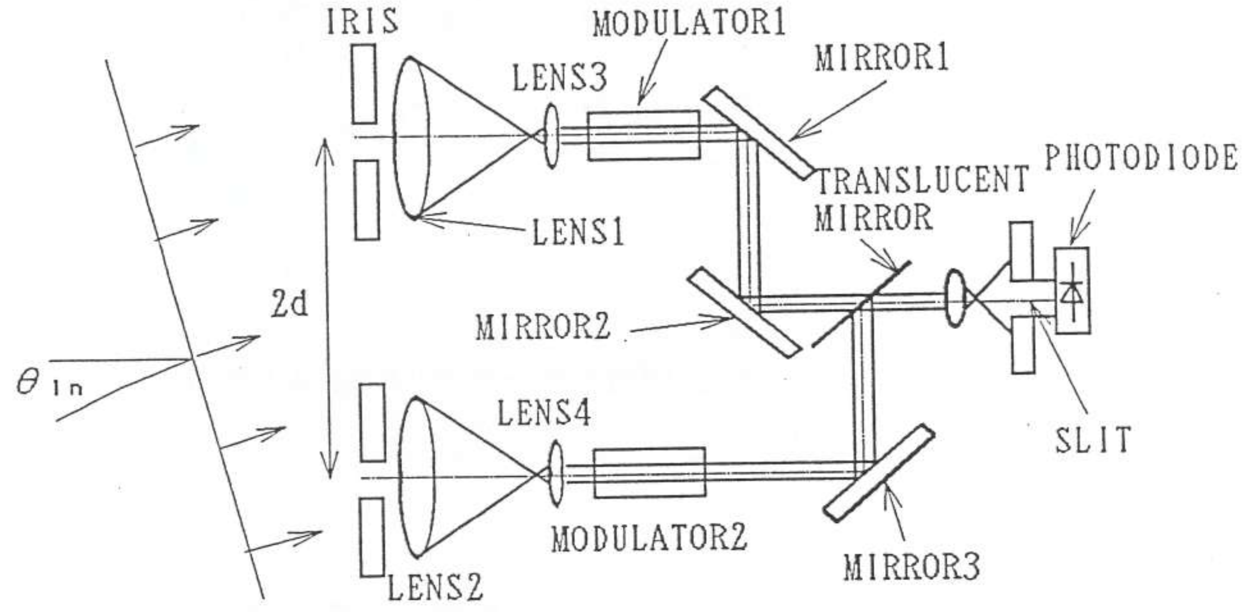
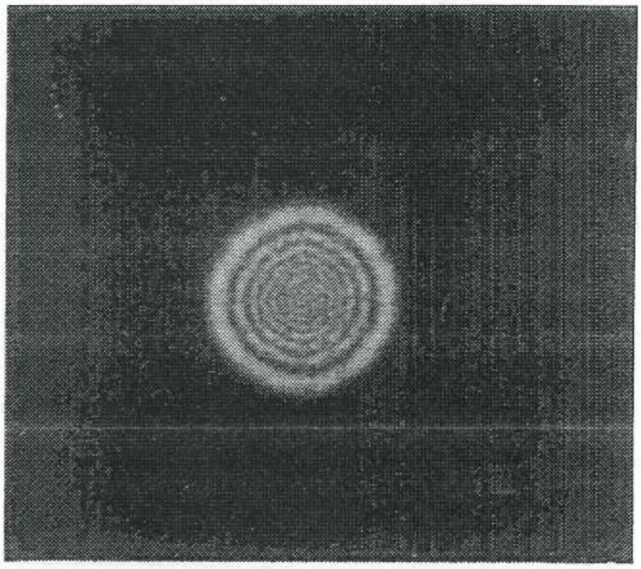
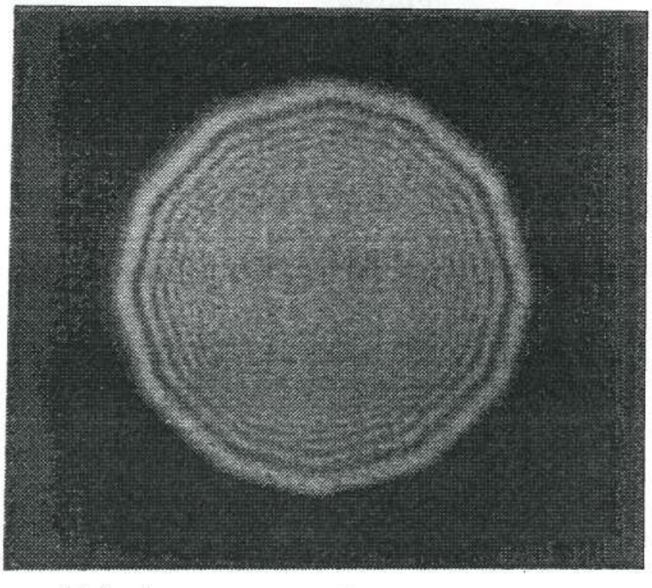


Fig. Configuration of a laser angle measurement system.



(a) Aperture diameter 5 mm



(b) Aperture diameter 10 mm

Fig. Photos of Fresnel diffraction patterns in the measurement system.

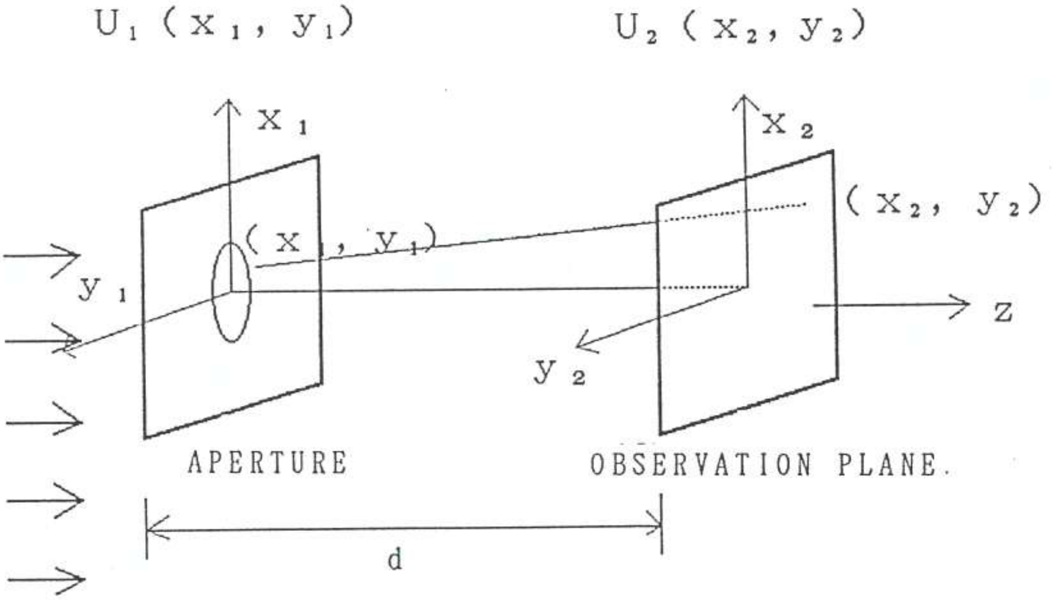
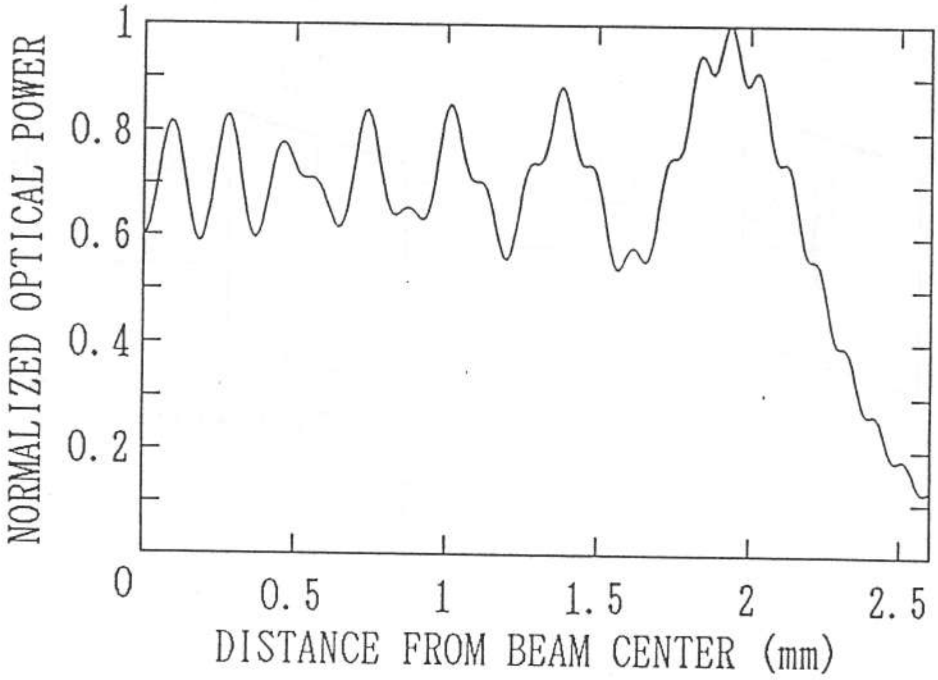
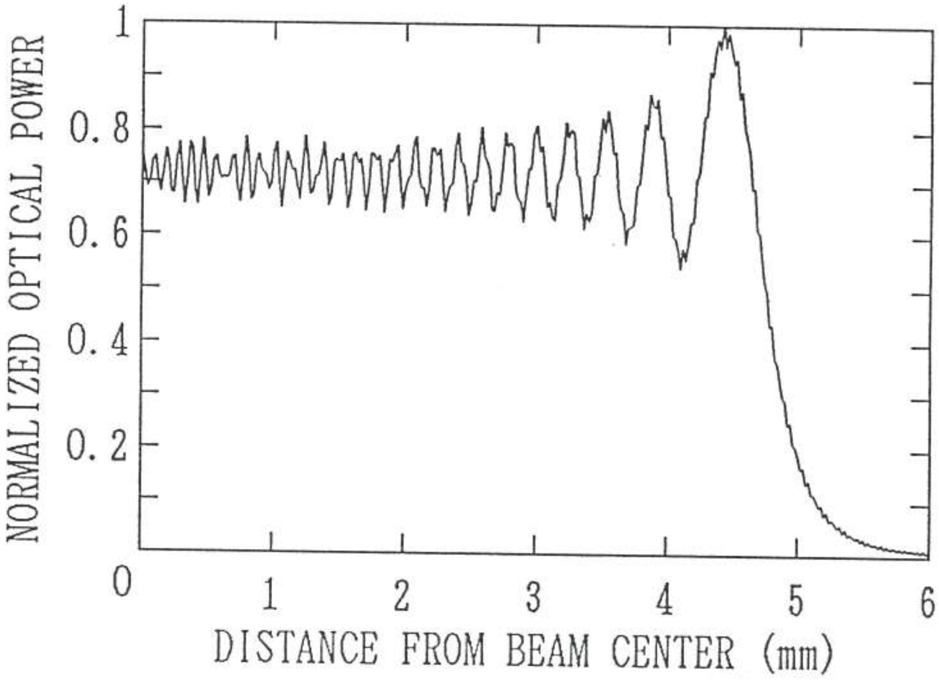


Fig. Coordinate system for diffraction analysis.

$$U_2(x_2, y_2) = \frac{je^{-jkl}}{\lambda l} \cdot \exp\left[-jk\frac{x_2^2 + y_2^2}{2l}\right]$$
$$\times \iint U_1(x_1, y_1) \exp\left[-jk\frac{x_1^2 + y_1^2}{2l}\right] \exp\left[j2\pi\frac{x_1x_2 + y_1y_2}{\lambda l}\right] dx_1dy_1$$

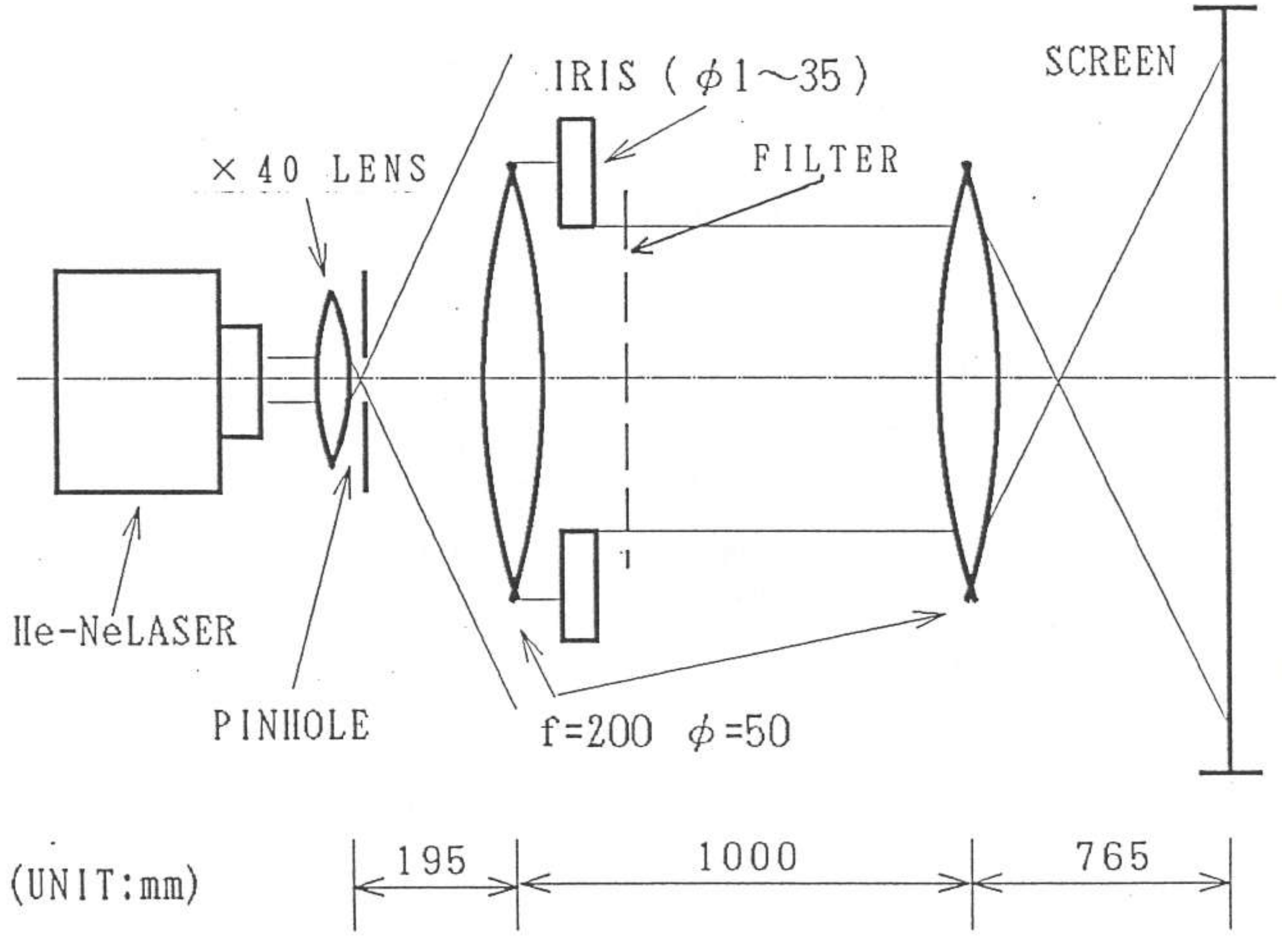


(a) Aperture diameter 5 mm

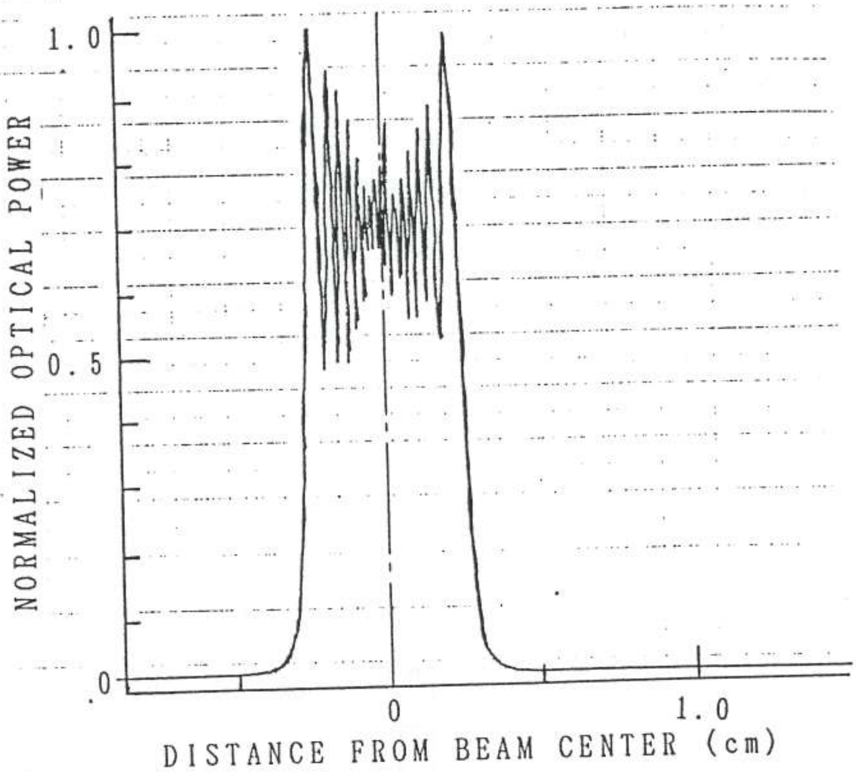


(b) Aperture diameter 10 mm

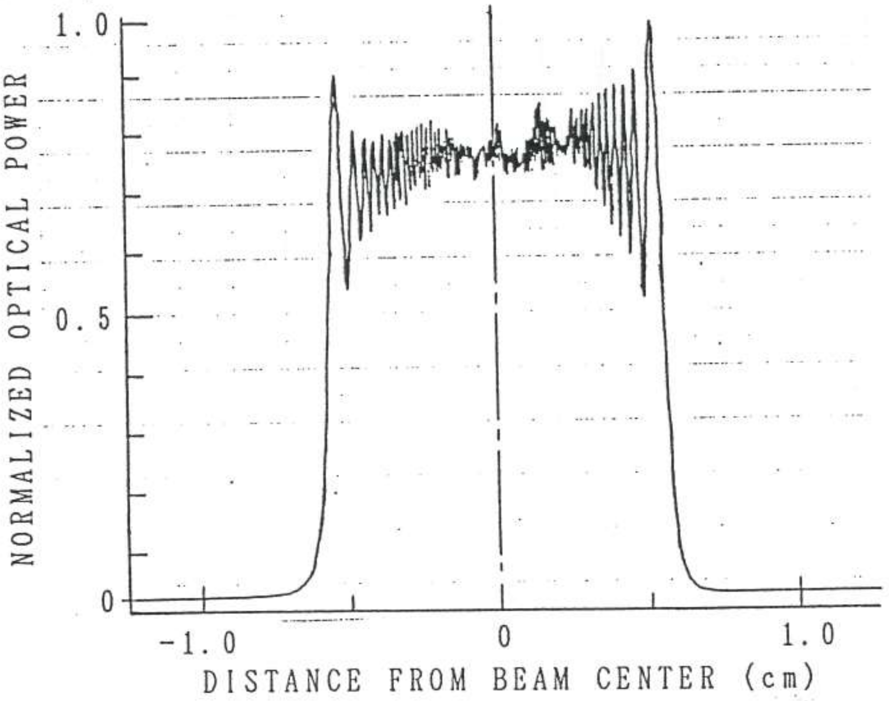
Fig. Calculated Fresnel diffraction patterns.



Fig, Measurement system of diffraction patterns.



(a) Aperture diameter 5 mm



(b) Aperture diameter 10 mm

Fig. Measured Fresnel diffraction patterns.

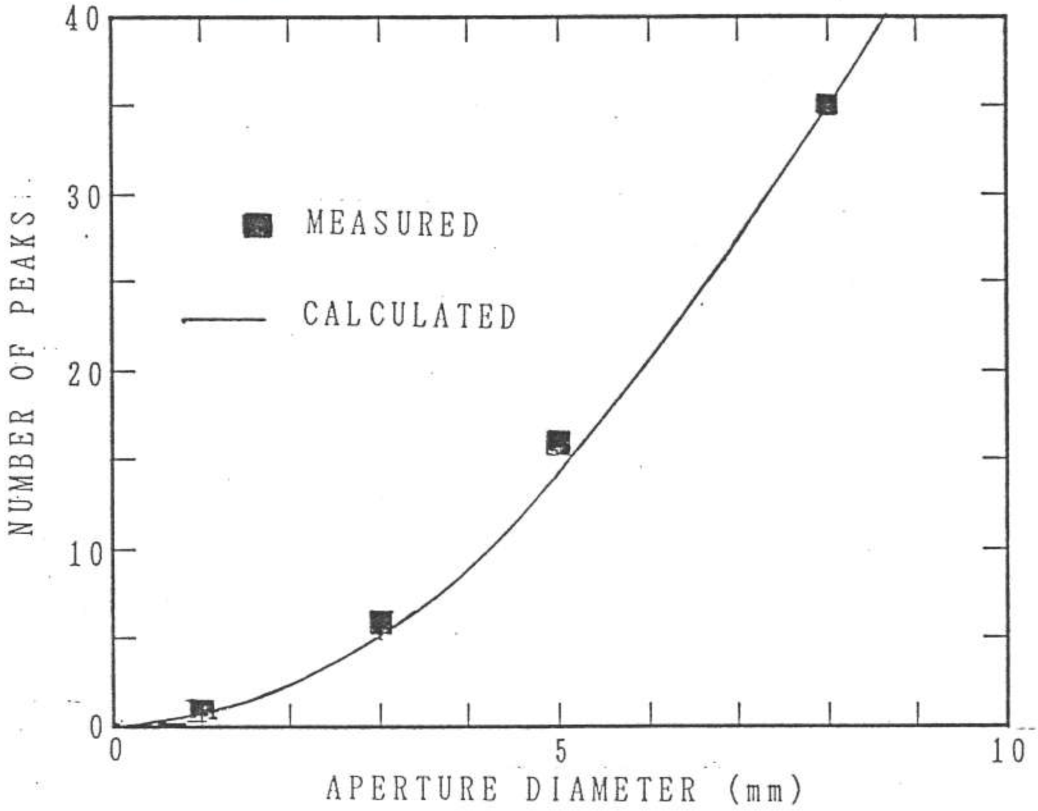
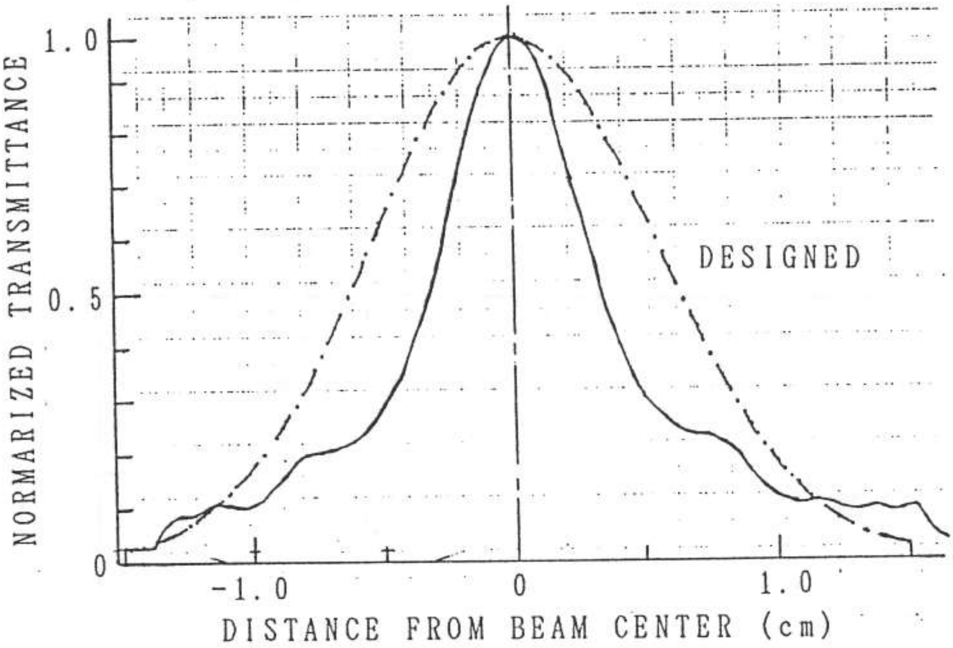
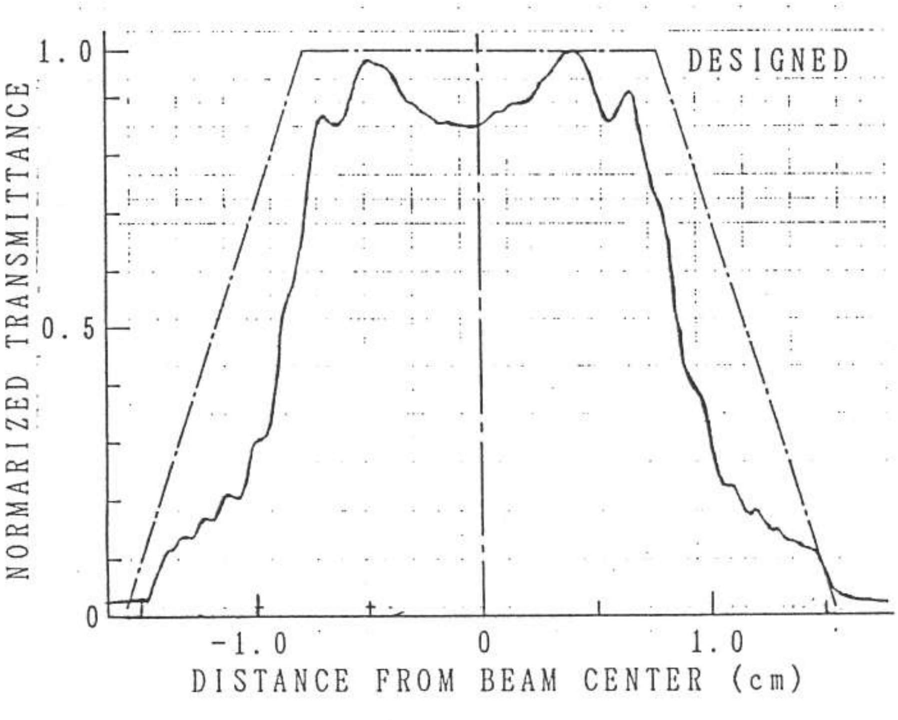


Fig. Relation between aperture diameter and peak number,



(a) Gaussian filter



(b) Trapezoidal filter

Fig. Transmissivity of filters.

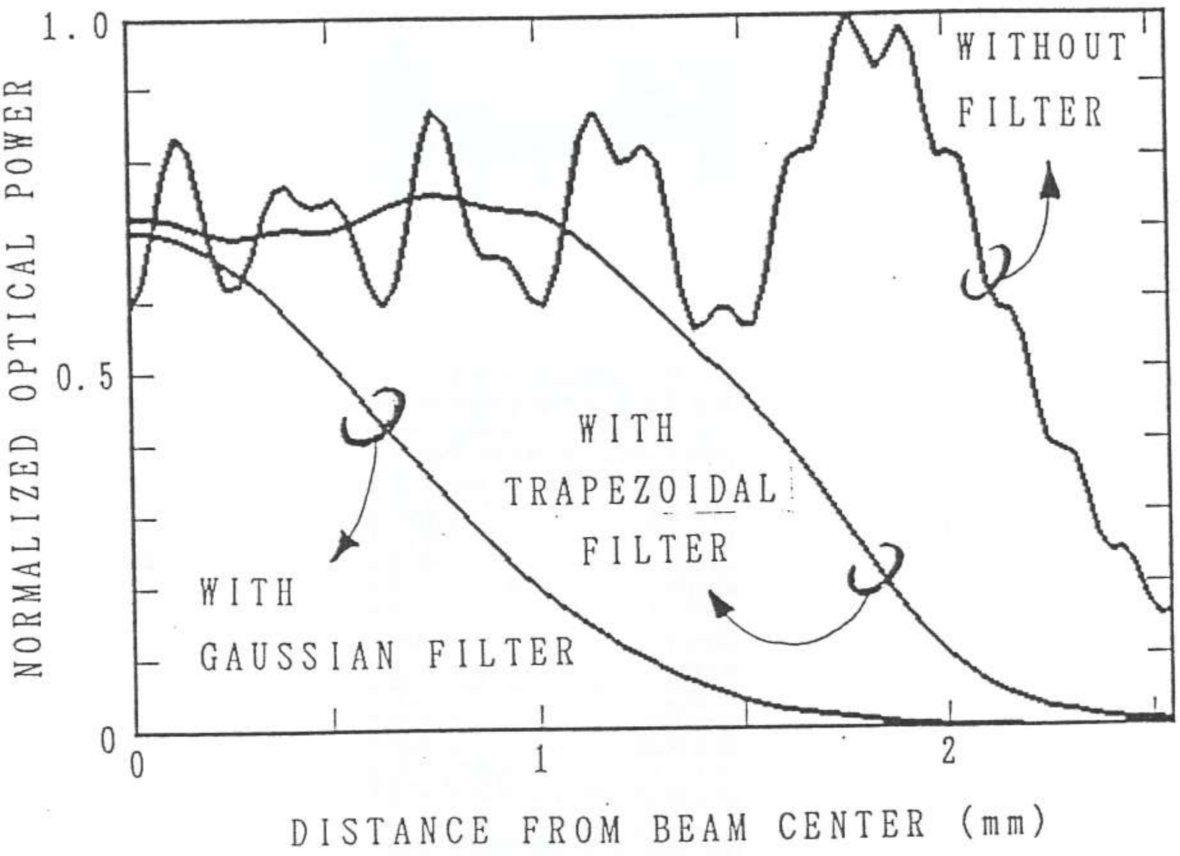
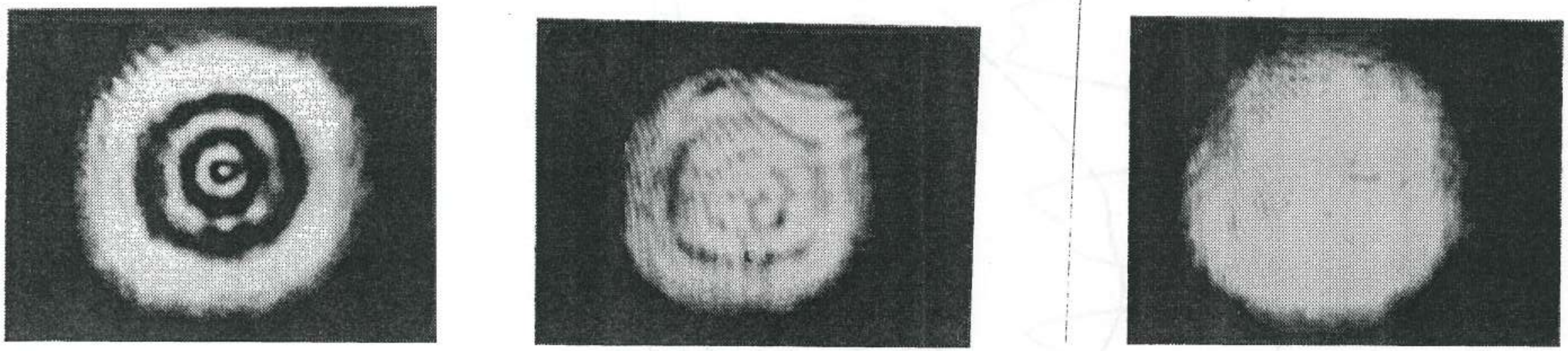


Fig. Beam profile improvement due to filters (calculated).



(a) Without filters (b) With Gaussian filters (c) With trapezoidal filters

Fig. Photos of beam interference patterns in the improved measurement system.

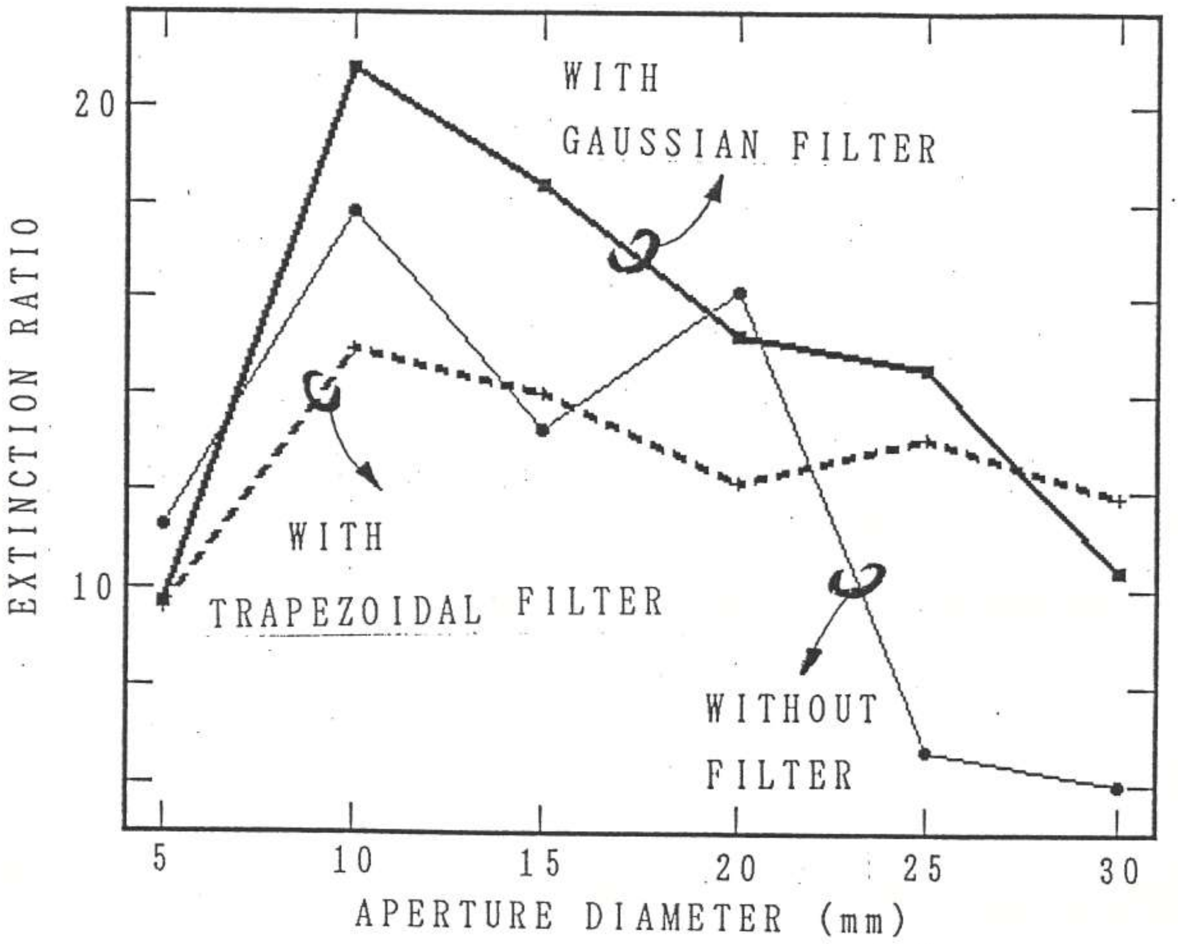


Fig. Extinction ratio improvement using filters.

CONCLUSIONS

1. No urgent need for ISL at ISAS at present.

2. Lunar lander/rover and tethered satellites are hopeful users in near future. Link analysis was given to show the possibility of higher bit rate transmission than a fiber cable system.

3. Status of a laser radar similar to ISL in ISAS.

4. Practical use of optical technologies :
   (1) Fiber harness in a satellite
   (2) Star tracker and star scanner

5. Basic investigation:
   (1) Quadrant detector radar: quadruple light sensor, for rendezvous use.
   (2) Laser angle gauge: interference + phase modulation, resolution of 10-7 rad. with 139 mm baseline.
   (3) Fresnel diffraction suppression in beams: spatial filters.

Authors Index

Authors Index