NASA CR-182268

Multiplexing Electro-Optic Architectures for Advanced Aircraft Integrated Flight Control Systems

IN-08
133980
p- 90

EOA
NASA-LEWIS
MCAIR
OPTIC SENSING TECHNOLOGY
EOA DESIGN CONCEPTS
ELECTRO-OPTIC ARCHITECTURE

FINAL REPORT

by
D. W. Seal

June 1989

McDonnell Douglas Corporation
McDonnell Aircraft Company
P.O. Box 516
St.Louis, MO 63166

Prepared for
National Aeronautics and Space Administration
NASA-Lewis Research Center
Cleveland, OH 44135

Contract NAS3-25345

NASA CR-182268

Multiplexing Electro-Optic Architectures for Advanced Aircraft Integrated Flight Control Systems

FINAL REPORT

by
D. W. Seal

June 1989

McDonnell Douglas Corporation
McDonnell Aircraft Company
P.O. Box 516
St.Louis, MO 63166

Prepared for
National Aeronautics and Space Administration
NASA-Lewis Research Center
Cleveland, OH 44135

Contract NAS3-25345

Report Documentation Page

NASA — National Aeronautics and Space Administration

1. Report No. NASA CR-182268	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle

Multiplexing Electro-Optic Architectures for Advanced Aircraft Integrated Flight Control Systems

5. Report Date: June 1989

6. Performing Organization Code

7. Author(s)

D. W. Seal

8. Performing Organization Report No.

10. Work Unit No.: 05-62-01

9. Performing Organization Name and Address

McDonnell Aircraft Company
P.O. Box 516
St. Louis, MO 63166

11. Contract or Grant No.: NAS3-25345

13. Type of Report and Period Covered: Final Report

12. Sponsoring Agency Name and Address

National Aeronautics & Space Administration
Lewis Research Center
Cleveland, OH 44135

14. Sponsoring Agency Code

15. Supplementary Notes

Project Manager, Mr. Robert Baumbick
NASA Lewis Research Center
Cleveland, OH 44135

16. Abstract

This report describes the results of a 10 month program sponsored by the National Aeronautics & Space Administration (NASA) under contract number NAS3-25345. The objective of this contract was to evaluate various optical sensor modulation technologies and to design an optimal Electro-Optic Architecture (EOA) for servicing remote clusters of sensors and actuators in advanced aircraft flight control systems. The EOAs supply optical power to remote sensors and actuators, process the modulated optical signals returned from the sensors, and produce conditioned electrical signals acceptable for use by a digital flight control computer or Vehicle Management System (VMS) computer. This study was part of a multi-year initiative under the Fiber Optic Control System Integration (FOCSI) program to design, develop, and test a totally integrated fiber optic flight/propulsion control system for application to advanced aircraft. Unlike earlier FOCSI studies, this program concentrated on the design of the EOA interface rather than the optical transducer technology itself.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Fiber Optic Sensors, fly-by-light, electro-optics, multiplexing architectures, wave division multiplex, time division multiplex, power-by-light	Unclassified

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price
Unclassified	Unclassified	89	

NASA FORM 1626 OCT 86

TABLE OF CONTENTS

TABLE OF CONTENTS (Concluded)

LIST OF PAGES

LIST OF ILLUSTRATIONS

LIST OF ABBREVIATIONS AND ACRONYMS

ADOCS	Advanced Digital/Optical Control System
APD	Avalanche Photo Diode
AWM	Awaiting Maintenance
AWP	Awaiting Parts
EMI	Electromagnetic Interference
EMP	Electromagnetic Pulse
EMT	Elapsed Maintenance Time
EOA	Electro-Optic Architecture
FACTS	Future Advanced Control Technology Study
FMCW	Frequency Modulated Continuous Wave
FOCSI	Fiber Optic Control System Integration
HI-REL	Air Force High Reliability Fighter Study
HSDB	High Speed Data Bus
ILS	Integrated Logistics Support
IOC	Initial Operational Capability
IR	Infra Red
LCC	Life Cycle Cost
LVDT	Linear Variable Differential Transducer
MCAIR	McDonnell Aircraft Company
MDC	McDonnell Douglas Corporation
MFHBF	Mean Flight Hours Between Failure
MoM	Measure of Merit
MSMD	Multiple Source/Multiple Detector
MSSD	Multiple Source/Single Detector
MTBF	Mean Time Between Failure
NASA	National Aeronautics and Space Administration
OTDR	Optical Time Domain Reflectometer
P3I	Pre-Planned Product Improvement
PBL	Power-By-Light
RFI	Request For Information
RVDT	Rotary Variable Differential Transducer
SELF	Self luminous
SMTD	STOL and Maneuvering Technology Demonstrator
SSMD	Single Source/Multiple Detector
SSSD	Single Source/Single Detector
STOL	Short Take-Off and Landing
TDIN	Time Division Intensity Normalized (TDM Analog)
TDM	Time Division Multiplex
TRD	Time Rate of Decay
VMS	Vehicle Management System
WDIN	Wave Division Intensity Normalized (WDM Analog)
WDM	Wave Division Multiplex

1.0 INTRODUCTION

This report describes the results of a 10 month program sponsored by the National Aeronautics and Space Administration (NASA) under contract number NAS3-25345. The objective of this contract was to evaluate various optical sensor modulation technologies and to design an optimal Electro-Optic Architecture (EOA) for servicing remote clusters of sensors and actuators in advanced aircraft flight control systems. The EOAs supply optical power to remote sensors and actuators, process the modulated optical signals returned from the sensors, and produce conditioned electrical signals acceptable for use by a digital flight control computer or Vehicle Management System (VMS) computer. This study was part of a multi-year initiative under the Fiber Optic Control System Integration (FOCSI) program to design, develop, and test a totally integrated fiber optic flight/propulsion control system for application to advanced aircraft. Unlike earlier FOCSI studies, this program concentrated on the design of the EOA interface rather than the optical transducer technology itself.

This program consisted of two primary tasks:

Task 1 - EVALUATION OF SYSTEMS

Task 2 - DETAILED DESIGN

Task 1 involved the definition of airframe optical sensor requirements, the design of candidate multiplexed EOAs, the establishment of architecture evaluation criteria and relative weighting factors, and the evaluation of candidate EOAs leading to the identification and selection of the optimal EOA designs for advanced aircraft. The results of Task 1 evaluation efforts indicate two points: (1) no singular optical sensor technology can be optimized for all aircraft sensor applications, and (2) due to the relatively immature state of optical sensor technology, no strong discriminator currently exists upon which to base the selection of an "optimal" EOA technology for any given sensor application. However, the results of Task 1 can be used to identify four "preferred" EOA technologies. These preferred technologies are:

- **Time Division Multiplexed Digital**
- **Time Division Multiplexed Analog**
- **Wave Division Multiplexed Optical Spectrum Analyzer**
- **Power-By-Light (PBL) Remote Electrical.**

Task 2 involved the conceptual design of the four candidate EOAs, layout of the sensors and EOAs to the flight controller interface, and identification of critical component technologies required to construct an all optical aircraft flight control system. The results of Task 2 design efforts indicate that it is possible to develop a set of four common EOA modules that are compatible with a wide range of promising optical sensor technologies.

2.0 BACKGROUND

Over the last 20 years, flight control technology has evolved from the original concept of mechanical control linkages with autopilot aiding to that of multi-disciplinary control integration technology. Control integration technology now encompasses several functional elements including flight control, propulsion control, weapons delivery, and displays. The concept of integrated control is to automate the coordination of these functional control elements to allow optimal coupling of the subsystems thereby reducing pilot workload, increasing aircraft performance, and enhancing overall mission effectiveness. Recent PAVE PILLAR advanced avionic architecture studies defined the fundamental concept of a Vehicle Management System (VMS) architecture as a means of achieving the required level of control integration for advanced aircraft.

Integration of interrelated functions such as flight and propulsion control would unlock significant performance, reliability, maintainability, and supportability benefits for emerging digitally controlled systems. Digital fly-by-wire technology combines sensors, effectors, and communications to provide a level of integration and performance not possible with mechanical flight control systems. Advanced digital fly-by-wire flight control systems can dramatically increase the operational flight envelope through faster control system response and increased number of active control surfaces. This increase in active control surfaces brings about a corresponding increase in sensor resources and the need for innovative management of these resources. Reliability of these systems becomes increasingly important as mechanical linkages are removed and buses, networks, and protocols are relied upon to provide the linkage for the physical integration of functional elements.

Requirements for increased levels of control integration coupled with the increased use of composite materials in advanced airframes will impose stringent electromagnetic susceptibility requirements that may mandate the use of fly-by-light avionic systems. Fiber optic technology offers numerous well known benefits including: high bandwidth, low weight, and immunity to man made threats such as Electromagnetic Interference (EMI), and Electromagnetic Pulse (EMP) generated by nuclear blasts. Commercial fiber optic research activities have led to the development of flight qualified fiber optic data networks but have not yet produced optical sensors acceptable for advanced aircraft.

DOD and NASA have recently sponsored several programs to promote research and development in the area of aircraft optical sensor technologies. Among these are the Advanced Digital/Optical Control System (ADOCS) program, Future Advanced Control Technology Study (FACTS 2000), and the Fiber Optic Control System Integration (FOCSI) program. FOSCI is a multi-year initiative to design, develop, and test a totally integrated fiber optic flight/propulsion control system for application to advanced aircraft. This EOA program marks the start of FOCSI Phase II and will provide the foundation for future activities in the areas of advanced component development and test.

3.0 TECHNICAL APPROACH

The objective of this contract was to evaluate various optical sensor modulation technologies and to identify the optimal EOA configuration for servicing remote multiplexed sensors in advanced aircraft flight control systems. Unlike earlier FOCSI studies, this program concentrated on the design of the multiplexed EOA interface rather than the optical transducer technology itself.

This program was composed of two primary tasks: 1) Evaluation of Systems, and 2) Detailed Design as described in the following paragraphs.

3.1 TASK 1 - EVALUATION OF SYSTEMS

In order to conduct a comprehensive evaluation of the candidate EOA systems, it was necessary to first define the operational and environmental requirements for a representative set of airframe optical sensors. Next an industry survey was conducted to establish a data base on currently available optical sensor technologies which served as the basis for the development of the candidate EOA designs. Architecture evaluation criteria and relative weighting factors were then established in order to compare the candidate EOA designs and identify the optimal EOA design configurations for advanced aircraft. Task 1 was composed of eight subtasks as outlined in the roadmap of Figure 3-1:

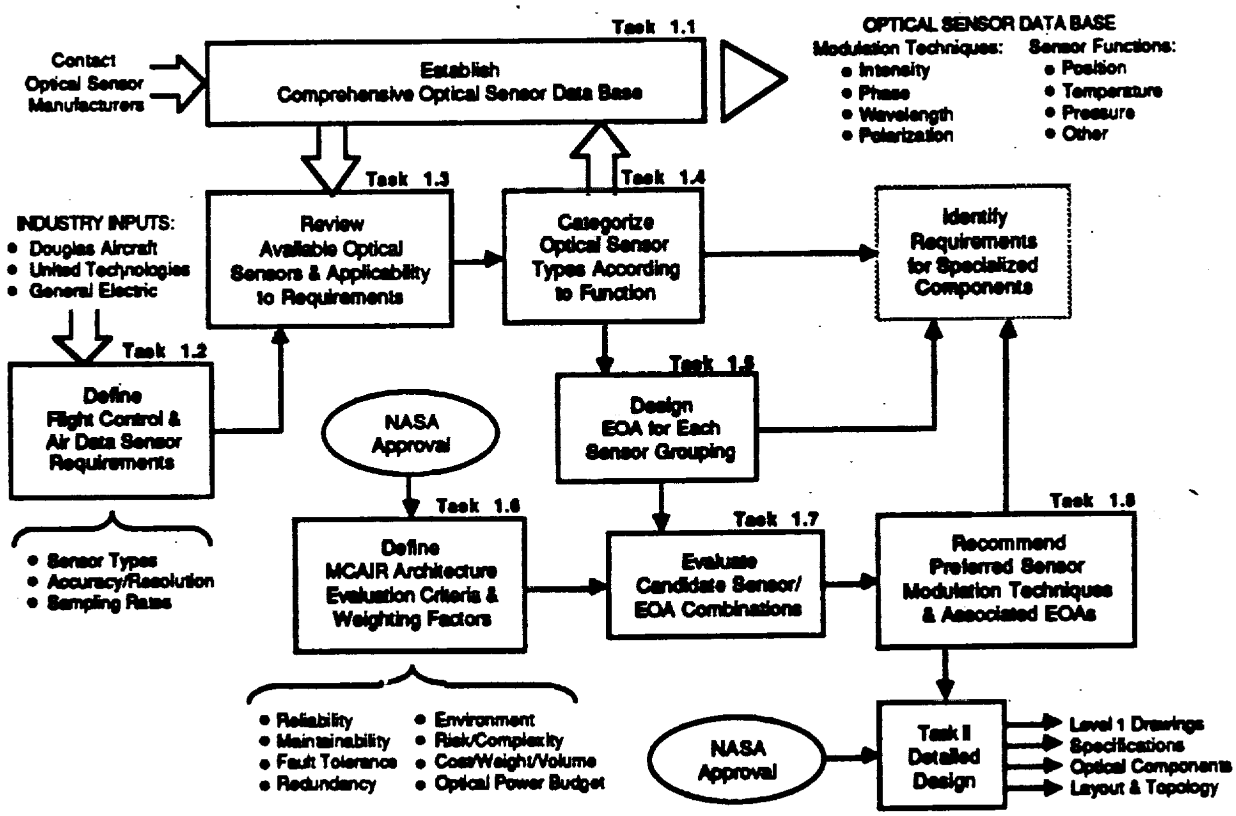


Figure 3-1. Task 1 Roadmap

3.1.1 Task 1.1 - Establish Comprehensive Optical Sensor Data Base

Previous efforts under the FOCSI Phase I and FACTS 2000 programs helped to establish a data base on optical transducer technologies primarily limited to aircraft propulsion applications. In a effort to establish a more comprehensive data base encompassing airframe as well as propulsion sensors, it was necessary to replicate many of the early FOCSI Phase I efforts.

More than 100 sensor manufacturers were contacted to solicit vendor inputs for the optical sensor data base. Based on product availability and related experience with fiber optics, 40 of these companies were subsequently issued a formal Request For Information (RFI) through the MCAIR contracts department. Manufacturers participating in the optical sensor data base are listed in Appendix A. Responses to the RFI and subsequent telephone surveys were compiled into a fiber optic sensor availability matrix similar to that developed under FOCSI Phase I. As shown in figure 3-2, the data base now encompasses over 100 optical sensors currently available from 40 manufacturers for all modulation techniques (intensity, phase, wavelength, polarization) and all anticipated flight and propulsion control applications.

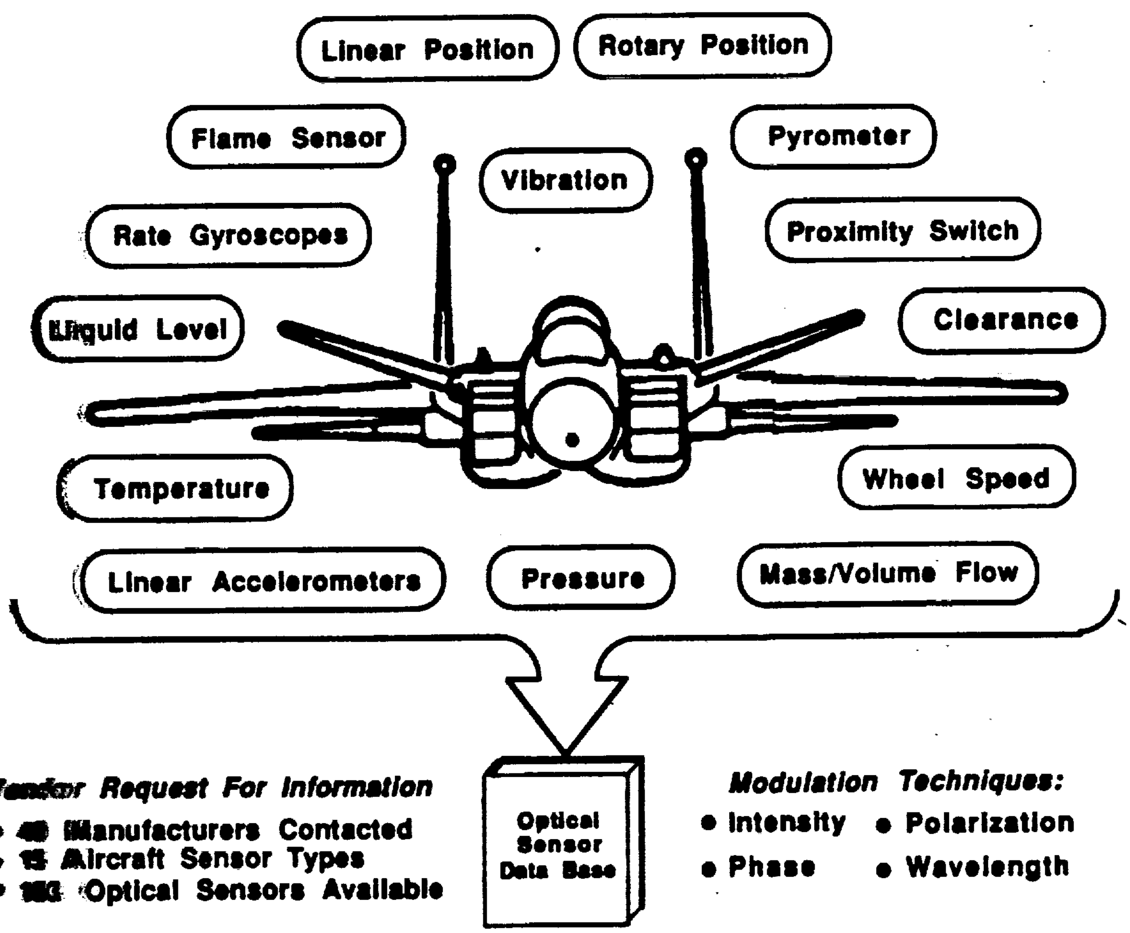


Figure 3-2 Optical Sensor Data Base

3.1.2 Task 1.2 - Define Flight Control and Air Data Sensor Requirements

This task defined the operational and environmental requirements for optical sensors installed in an advanced fighter aircraft. The operational requirements included sensor range, accuracy, resolution, and update rate. Environmental requirements included temperature, altitude, and vibration. The F-15 STOL and Maneuvering Technology Demonstrator (F15/SMTD) aircraft was selected as the point design for establishing the flight control and air data sensor requirements. This aircraft was selected because it is representative of the class of high performance fighter aircraft which are expected to benefit from the use of fiber optic sensor technology. The F-15/SMTD aircraft is a totally fly-by-wire aircraft which incorporates variable canards, 2-D thrust vectoring nozzles, thrust reversing vanes, and direct drive electrical force motor actuators to achieve a high degree of maneuverability. The F-15/SMTD architecture, shown in Figure 3-3, represents a first generation approach to an integrated control system. A quad redundant digital flight controller with continuous cross channel data monitoring provides a high degree of fault tolerance to ensure system integrity. Integration of the flight and propulsion control subsystems is accomplished through a MIL-STD-1553B compatible multiplex data bus.

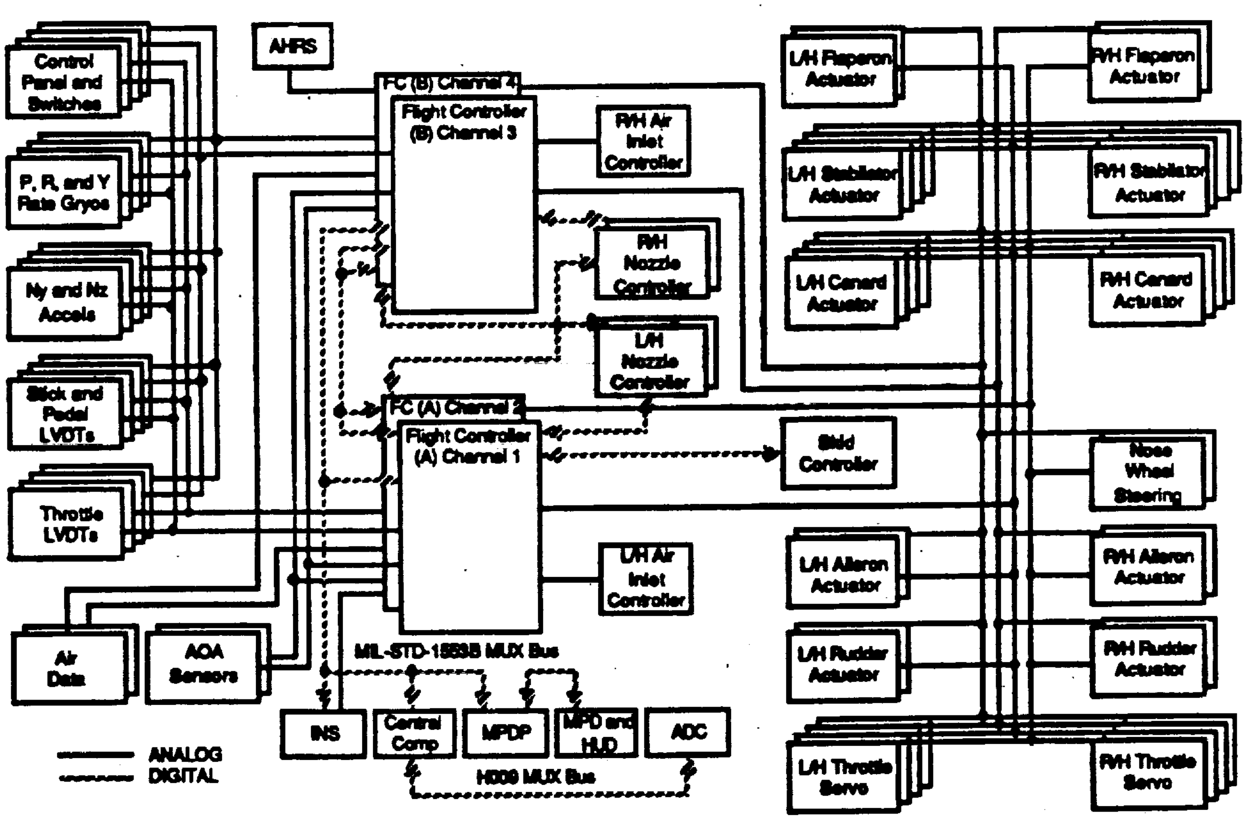


Figure 3-3. F-15/SMTD Flight Control System Architecture

A total of 126 flight control and air data sensors were identified as candidates for replacement with electro-optic sensors. As shown in Figure 3-4, these sensors can be grouped into the following 7 sensor functional types:

1) Linear Accelerometers
2) Rate Gyroscopes
3) Linear Position Sensors
4) Rotary Position Sensors
5) Air Data Pressure Sensors
6) Rotary Wheel Speed Sensor
7) Air Data Temperature Sensors

SENSOR FUNCTION		SENSOR REDUNDANCY				
TYPE	NAME	SYMBOL	LEFT	CENTER	RIGHT	TOTAL
Linear Accelerometer	Lateral Acceleration	NY	2		2	8
	Normal Acceleration	NZ	2		2	
Rate Gyroscope	Aircraft Pitch Rate	PITCH	2		2	12
	Aircraft Roll Rate	ROLL	2		2	
	Aircraft Yaw Rate	YAW	2		2	
Linear Position	Roll Stick Position	RSP		4		74
	Pitch Stick Position	PSP		4		
	Yaw Pedal Position	YPP		4		
	Throttle Lever Angle	TLA	4		4	
	Aileron	AIL	2		2	
	Flaperon	FLAP	2		2	
	Canard	CNRD	4		4	
	Stabilator	STAB	4		4	
	Nose Wheel Steering	NWS		2		
	Air Inlet Controller	AIC	2		2	
	Nozzle Controller	NC	8		8	
	Thrust Reverser Vane	TRV	4		4	
Rotary Position	Angle Of Attack	AOA	4		4	20
	Rotary Rudder	RUD	2		2	
	Power Lever Angle	PLA	4		4	
Pressure	Pitot Pressure	PT	2		2	8
	Static Pressure	PS	2		2	
Speed	Main Landing Gear	MLG	1		1	2
Temperature	Air Data Temperature	ADT	1		1	2

TOTAL SENSORS FOR FULL REDUNDANCY = 126

Figure 3-4. Aircraft Sensor Functional Groupings

The most common type of aircraft sensor is the linear position sensor. This sensor in electrical form is referred to as a Linear Variable Differential Transducer (LVDT). The next most common sensor is the Rotary Variable Differential Transducer. (RVDT). LVDTs are generally less complicated to manufacture and have proven to be more reliable than RVDTs, and as a result are generally used for position sensing whenever possible throughout the aircraft.

Sensor Operational Requirements for each of the optical sensors identified in Figure 3-4 were obtained from procurement specifications for the equivalent analog electrical sensors in the F-15/SMTD aircraft. These operational requirements are detailed in Figure 3-5. By dividing the total sensor range parameter by the lowest resolution detectable for each analog sensor, it is possible to determine the equivalent resolution requirements for a digital sensor system. The linear and rotary position sensors were all found to have an equivalent digital resolution of 12 bits. The linear accelerometer, rate gyroscope, pressure, temperature, and wheel speed sensors all have an equivalent digital resolution of 16 bits. This difference can largely be attributed to the individual resolution of the Analog-to-Digital converters used to digitize the incoming analog signals. As indicated by the sensor accuracy requirements outlined in Figure 3-5, the extreme accuracy (< 1%) normally associated with a digital sensor system is not generally required for flight control applications. Since the aircraft employs a closed loop feedback control system, minor sensor inaccuracies tend to be factored out and do not affect the overall handling qualities. The fact that the pilot himself is an integral part of the flight control feedback loop, will also tend to minimize the need for digital sensor accuracy. The sensor update rates listed in the table reflects the rate that sensor information is currently supplied to the flight controller for use in flight control law execution. The sensor update rate may be as high as 1 KHz at the actuator servo interface in order to maintain stable control.

SENSOR			SIGNAL			
TYPE	SYMBOL	NUM	RANGE	RESOLUTION	ACCURACY	RATE
Linear Accelerometer	NY	4	+/-2 G's	0.0002 G's	+/-2.5% -15°C TO +30°C (see Note 1)	40 Hz
	NZ	4	+/-10 G's	0.0020 G's		80 Hz
Rate Gyroscope	PITCH	4	+/-60 deg/second	0.005 deg/s		80 Hz
	ROLL	4	+/-300 deg/second	0.010 deg/s		80 Hz
	YAW	4	+/-60 deg/second	0.005 deg/s		40 Hz
Linear Position	BSP	4	+/-1.15 Inch	0.00562 In	+/-3% of Reading @ 68°F (see Note 2)	80 Hz
	PSP	4	-.82 to +1.54 Inch	0.000576 In		80 Hz
	YPP	4	+/-1.75 Inch	0.000854 In		40 Hz
	TLA	8	0 to 56 degrees	0.01367 deg	+/- 1% FS	40 Hz
	AIL/FLAP	4 / 4	+/-0.685 Inch	0.000335 In	+/- 1% FS at 68°F (see Note 3)	20 Hz
	CNRD/STAB	8 / 8	+/-3.889 Inch	0.001899 In		20 Hz
	NWS	2	+/-1.667 Inch	0.000814 In		20 Hz
	A/C	4	+/-4.425 Inch	0.002161 In		50 Hz
	NC	16	+/-7.5 Inch	0.003662 In	+/-0.33% -40°F to +275°F	50 Hz
	TRV	8	+/-2.00 Inch	0.000977 In		50 Hz
Rotary Position	AOA	8	-19 to +56 degrees	0.02800 deg	0.15% FS	40 Hz
	RUD	4	+/-30.5 degrees	0.01489 deg	+/-1.5% FS (see Note 3)	20 Hz
	PLA	8	+/-68 degrees	0.03320 deg		20 Hz
Pressure	PT	4	0 to 55 Inches Hg	0.0010 In Hg	0.07 +/-0.2%	40 Hz
	PS	4	0 to 38 Inches Hg	0.0005 In Hg	0.06 +/-0.2%	40 Hz
Speed	MLG	2	0 to 655 ft/second	0.02 ft/sec		20 Hz
Temperature	ADT	2	-65°F to +440°F		+/- 3 Degrees	8.3 Hz

NOTES: 1) Linearity = 1% FS. (Add +/- 0.4% per °C for Operation Between -54 °C and +71 °C)
2) Linearity = 1.23%. (Add 1.5% FS for Operation Between -65 °F and +203 °F)
3) Accuracy = +/- 1.5% per 100 °F for Operation Between -40 °F and +275 °F

Figure 3-5. Aircraft Fiber Optic Sensor Requirements

Sensor Environmental Requirements for all locations on the F-15/SMTD aircraft were obtained from a report entitled "F-15 Vibration, Shock, and Acoustic Design Requirements and Test Procedures for Aircraft Equipment, Update Based on Ground and Flight Test Measurements" (report number MDC A4246). This report outlined environmental conditions for all regions of the aircraft. Environmental data is based upon MIL-STD-810 aircraft environments with modifications based upon actual F-15 ground and flight test data. Environmental requirements for each the seven functional sensor groupings were identified as indicated in Figure 3-6. As expected, the engine bay provides the harshest operating environment for sensors. Temperature within the engine bay on the F-15/SMTD aircraft may reach +475 degrees Fahrenheit. Flight control actuation sensors, on the other hand, are generally rated at +275 degrees Fahrenheit due to a thermal heating effect caused by the recirculating hydraulic fluid used to drive the actuators. These temperatures reflect operation of the F-15/SMTD aircraft during supersonic dash operation. Advanced aircraft with sustained supersonic cruise capability may experience even greater temperature extremes.

SENSOR		ENVIRONMENT	
TYPE	SYMBOL	TEMPERATURE	PRESSURE
Linear Accelerometer	NY NZ	-65°F to +160°F	Pressurized
Rate Gyroscope	PITCH ROLL YAW	-65°F to +160°F	Pressurized
Linear Position	RSP/PSP YPP/TLA	-65°F to +203°F	Pressurized
	AIL FLAP CNRD STAB NWS	-40°F to +275°F	Unpressurized Sea Level to 50K ft
	A/C N/C TRV	-40°F to +275°F -40°F to +475°F -40°F to +475°F	Unpressurized Sea Level to 50K ft
Rotary Position	AOA	-65°F to +160°F	Sea Level to 50K ft
	RUD PLA	-40°F to +275°F	
Pressure	PT PS	-65°F to +160°F	Sea Level to 50K ft
Speed	MLG	-65°F to +160°F	Sea Level to 50K ft
Temperature	ADT	-65°F to +160°F	Sea Level to 50K ft

(1) **Numbers In Parenthesis Represent Gunfire Vibration Levels (Refer to Report MDC A4246 for Vibration Test Data)**

Figure 3-6. Aircraft Fiber Optic Sensor Environments

Sensor Vibration Requirements will vary depending on the exact location of the sensor within the airframe. Figure 3-7 indicates the vibration levels that might be encountered for specific locations on the aircraft. These levels indicate the worst case vibration levels for continuous operation of the sensors. The sensors should be capable of surviving when exposed to higher vibration levels, but are only required to to meet operation performance requirements during the vibration levels below.

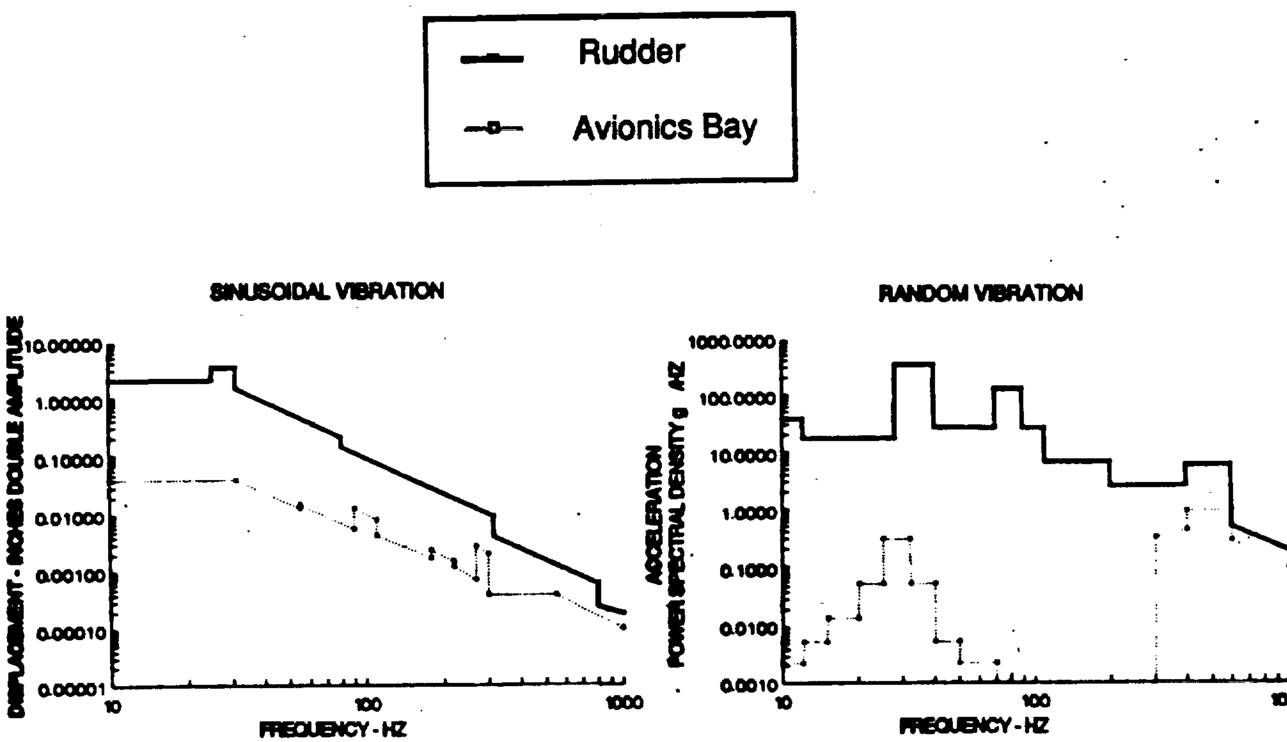
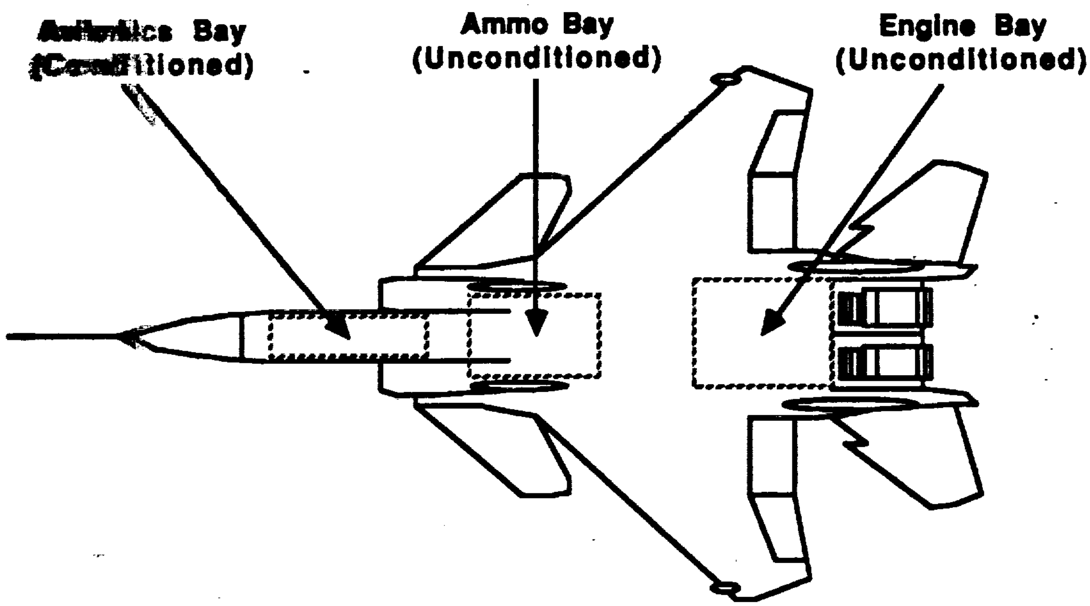


Figure 3-7 Fiber Optic Sensor Vibration Levels

EOA Environmental Requirements - In addition to defining the sensor operational and environmental requirements, it was also necessary to define these requirements for the EOAs. Although sensors may be located anywhere throughout the aircraft, production EOA systems would typically be confined to one of three locations within the aircraft; the avionics bay, the ammunitions bay, or the engine bay. Environmental requirements for each of these areas are outlined in Figure 3-8.



BAY DESCRIPTION	ENVIRONMENT	
	TEMPERATURE	PRESSURE
Avionics Bay	-65°F to +160°F	Pressurized
Ammo Bay	-65°F to +160°F	Sea Level to 50K ft
Engine Bay	- 65°F to +475°F	Sea Level to 50K ft

(1) Numbers in Parenthesis Represent Gunfire Vibration Levels (Refer to Report MDC A4246 for Vibration Test Data)

Figure 3-8 Sensor Electronics Bay Area Environment

EOA Vibration Requirements will vary depending on the exact location of the EOA within the airframe. Figure 3-9 indicates the vibration levels that might be encountered for specific locations on the aircraft. These levels indicate the worst case vibration levels for continuous operation of the EOAs. The EOAs must be capable of surviving when exposed to higher vibration levels, but are only required to to meet operation performance requirements during the vibration levels below.

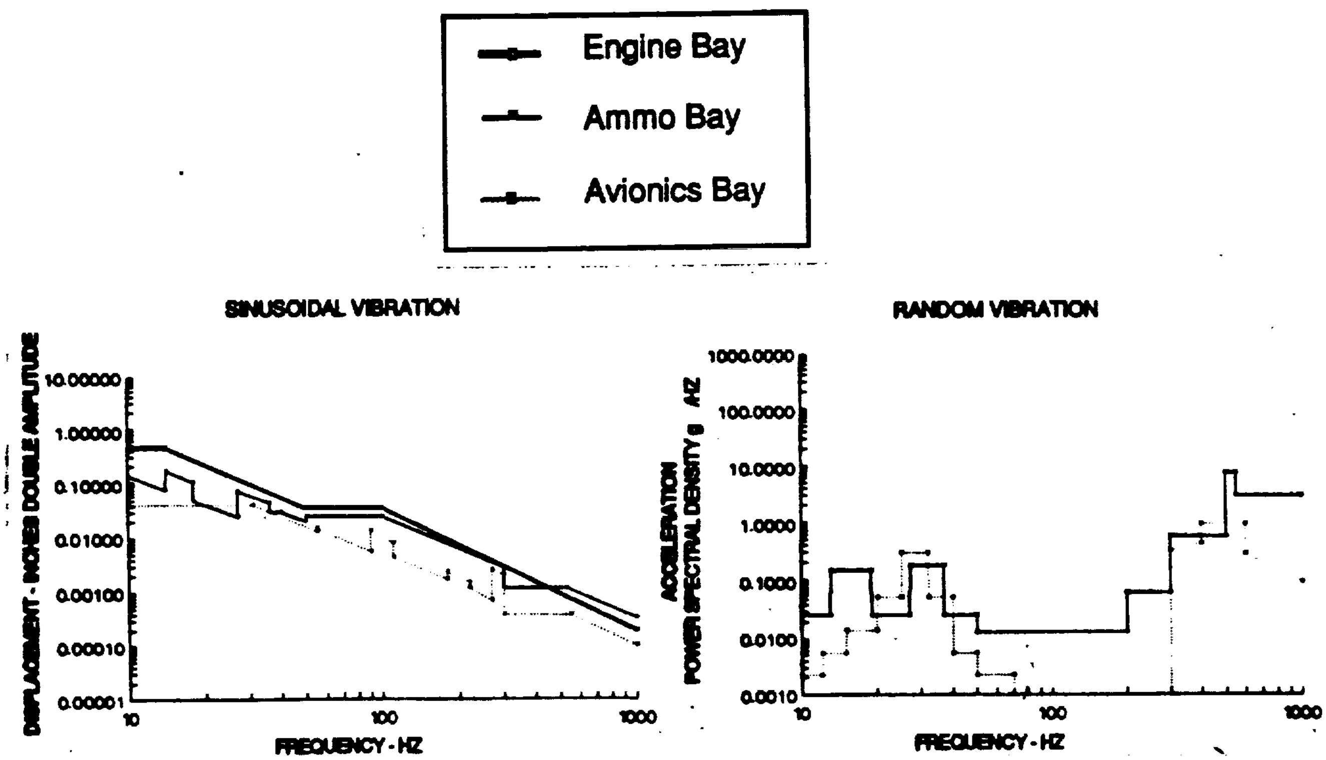


Figure 3-9 Sensor Electronics Bay Area Vibration Levels

3.1.3 Task 1.3 - Review Available Optical Sensors and Applicability to Requirements

The original intent of this task was to interrogate the optical sensor data base established under Task 1.1 to determine the current availability of optical sensors which meet the flight control and air data sensor requirements identified under Task 1.2. Although numerous sensors in the data base were capable of meeting the operational requirements, none have been tested at the environmental extremes required for fighter aircraft. This is due to the relative immaturity of optical sensor technology and the fact that extensive environmental testing has not yet been conducted on the limited number of prototype optical sensors currently available. The scope of this task was subsequently changed to incorporate data from the FACTS 2000 fiber optic sensor study in an effort to ensure that all possible sensor modulation technologies which hold promise for advanced aircraft would be evaluated. The optical sensor data base was then interrogated to determine which of the available sensor technologies could meet the operational performance requirements. The optical sensor data base was then re-organized according to sensor modulation technology and associated sensor function. In instances where more than one modulation scheme is feasible, multiple candidate sensors were selected. The resulting list of candidate sensors is presented in Figure 3-10.

	Rotary Position	Linear Position	Angular Velocity	Tachometer/ Shaft Speed	Linear Acceleration	Temperature	Pressure	Flow (Mass)	Flow (Volume)	Liquid Level	Pyrometer	Flame Sensor	Clearance	Proximity Switch	Vibration
TDM Digital Optical Code Plate	●	●					●								
WDM Digital Optical Code Plate	●	●													
Analog Gradient Filter Plate	●	●													
Beam Interrupt/Pulse Count	●	●		●											●
Microbend Modulated					●		●								●
Absorption Edge Shift						●									
Reflective Diaphragm						●	●	●	●				●	●	●
Near Total Internal Reflection										●					
Raman/Raleigh Backscatter						●									
Blackbody Radiation						●									
Passive IR Analysis						●					●	●			
Fabry-Perot Interferometer						●	●								
Phosphorescent						●									
Fluorescent						●									
Moving Diffraction Grating							●								
Michelson Interferometer							●								
Mach-Zehnder Interferometer					●										●
Sagnac Interferometer			●			●									
Photo-Elastic							●								
Power-By-Light (PBL)	●	●				●								●	

Figure 3-10 Fiber Optic Sensor Technology Availability

3.1.4 Task 1.4 - Categorize Optical Sensors According to Function

This task categorized the available optical sensors identified under Task 1.3 according to modulation technique and sensor functional type in order to determine which modulation techniques are best suited for each sensor application. This was accomplished by comparing the aircraft sensor functional groupings (Figure 3-4) against the currently available optical sensor modulation technologies (Figure 3-10) to identify the candidate optical sensor technologies for aircraft flight control applications. These candidate fiber optic sensor technologies are shown in Figure 3-11.

CANDIDATE FIBER OPTIC SENSORS			POTENTIAL	
TYPE	TECHNOLOGY	REFERENCE	NO	YES
Linear Accelerometer	Microbend Modulated	WDIN		X
	Mach-Zehnder Interferometer	FMCW		X
Rate Gryoscope	Sagnac Interferometer	FMCW		X
Linear/Rotary Position (N=10)	Digital Optical Code Plate	TDM		X
		WDM		X
	Analog Gradient Filter Plate	TDIN		X
		WDIN		X
	Beam Interrupt/Pulse Count	TDM	N/A	
	Power-By-Light (PBL)	LEDs		X
Pressure (N=4)	Digital Optical Code Plate	TDM		X
	Microbend Modulated	TDIN		X
		WDIN		X
	Reflective Diaphragm	WDIN		X
	Fabry-Perot Interferometer	WDIN		X
		WDM		X
	Moving Diffraction Grating	WDM		X
	Michelson Interferometer	FMCW		X
	Photo-Elastic	WDIN		X
		WDM		X
Speed	Beam Interrupt/Pulse Count	TDM		X
Temperature (N=2)	Absorption Edge Shift	TDIN		X
		WDIN		X
	Raman/Raleigh Backscatter	OTDR		X
	Blackbody Radiation	SELF	N/A	
	Passive IR Analysis	SELF	N/A	
	Fabry-Perot Interferometer	WDIN		X
	Phosphorescent	TRD		X
	Fluorescent	TRD		X
	Sagnac Interferometer	FMCW		X
	Power-By-Light (PBL)	LEDs/Laser		X

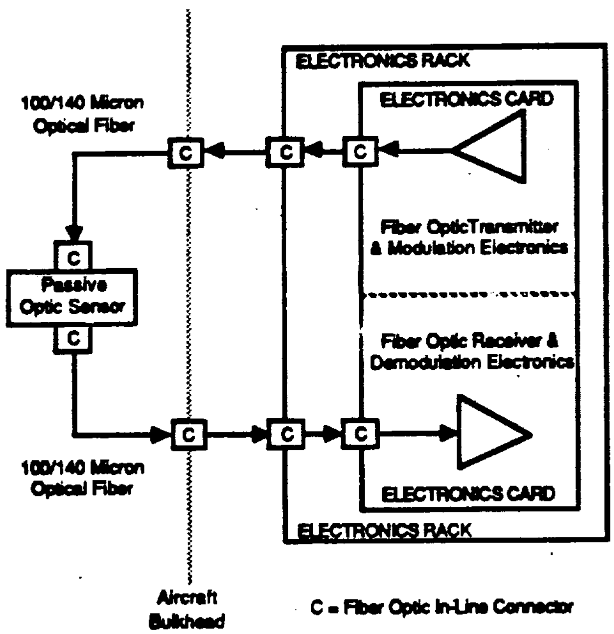
Figure 3-11 Candidate Fiber Optic Sensor Technologies

Without specific consideration to sensor operating environment, it is difficult to define a valid discriminator with which to select an "optimal" sensor technology for any given application. However, the sensor operational requirements outlined in Task 1.2. can be used to identify these sensor technologies which are unacceptable for flight control applications. One unacceptable technology is that used in the beam interrupt/pulse count type position sensor. These type of sensors are generally referred to as "incremental" position sensors because they require knowledge of the initial sensor position and then count the returned pulses from the sensor to determine final position relative to the known starting point. The initial sensor position or "null" must be set upon power-up by driving the sensor through its entire sensing range to establish endpoints. Incremental position sensing requires continuous monitoring of the returned signals to maintain position knowledge and is therefore not acceptable for a multiplexed flight control system. Incremental sensors are widely used for continuous position sensing in industrial process controllers. Although the beam interrupt/pulse count sensor is not acceptable for absolute position sensing, it can be effectively used as a tachometer to detect rotary wheel speed. The tachometer can be effectively multiplexed since it needs only to sample the returned signal for a short period of time to determine speed.

The self-luminous sensor is also unacceptable for flight control applications. Two types of self-luminous temperature sensors were evaluated: a passive Infra Red (IR) analysis type sensor, and a blackbody radiator. Both of these temperature sensors operate on the principle of radiated spectral emission as described by the Planck equation. Self-luminous sensors are typically uncomplicated but can provide extremely accurate temperature measurements. According to Figure 3-5, the air data temperature sensor currently operates in the range of -65 to +440 degrees Fahrenheit. Due to the difficulty in detecting spectral energy at extremely low temperatures, currently available self-luminous sensors are constrained to a minimum operating temperature of approximately +900 degrees Fahrenheit.

3.1.5 Task 1.5 - Design EOA for Each Sensor Group

This task developed multiplexed EOA suitable for each of the candidate sensor types identified under Task 1.4. The principle consideration in the design of an EOA is the selection of an optical multiplexing technique which accommodates the largest number of sensors while maintaining an adequate optical power margin. The key elements that determine overall optical power budget are: source power level, network losses, receiver sensitivity, and the signal to noise ratio required to achieve the desired level of sensor performance. A representative power budget analysis for a typical passive optical sensor installed in an aircraft is shown in Figure 3-12.



LOSS BUDGET ANALYSIS:

MINIMUM INTERCONNECT LOSSES:

Connectors:	8 Connectors
	x 2.0 dB/Connector
	16.0 dB

Minimum Interconnect Loss: 16.0 dB (1)

ADDITIONAL LOSSES:

Manufacturing Splice:	1.0 dB
Repair Splice:	4.0 dB (2 x 2.0 dB)
Additional Bulkeads:	6.0 dB (3 x 2.0 dB)
Connector Contamination:	0 - 8 dB
Temperature Effects:	2.0 dB
Vibration Effects:	0 - 3 dB
Connector/Fiber Ageing:	2.0 dB
Total Additional Losses:	15.0 - 26.0 dB

Minimum Safety Margin: 15.0 dB (2)

Minimum Loss Budget: 31.0 dB (16.0 + 15.0)

(1) Interconnect Loss Analysis Does Not Include Sensor Insertion Loss or Interconnect Cable Losses

(2) Minimum Optical Safety Margin to Cover Additional Losses = 15.0 dB (Navy A-12 Requirement)

Figure 3-12 Passive Optical Sensor Power Budget Analysis

A minimum interconnect loss budget of 16 db is required to overcome the fixed optical losses associated with the manufacture of a connectorized passive optical sensor system. An additional minimum safety margin of 15 dB is required to accommodate the various optical losses expected to occur over the anticipated 20 year service life of the aircraft. This power budget analysis is based upon actual field experience with fiber optics installed in AV-8B production aircraft, and represents the minimum loss configuration for a non-multiplexed passive optical sensor system. Insertion of any multiplexing device (optical switch, optical coupler, etc.) into the optical path will increase overall system loss by an amount equal to the insertion loss of the device installed plus losses associated with the optical connectors on the device itself.

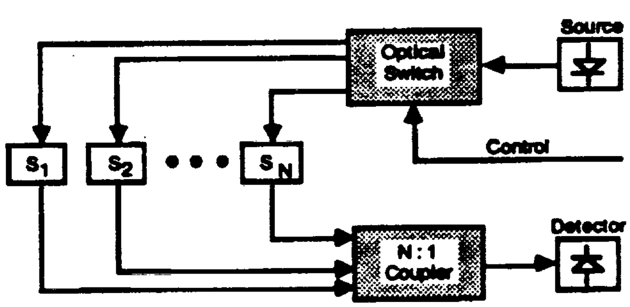
Several optical multiplexing techniques were considered in the design of each EOA. These techniques include:

SSSD - Single Source/Single Detector approach
SSMD - Single Source/Multiple Detector approach
MSSD - Multiple Source/Single Detector approach
MSMD - Multiple Source/Multiple Detector approach

Each of these multiplexing techniques were evaluated to determine applicability to a multiplexed aircraft flight control system. Evaluation criteria included optical power budget, EOA complexity, and requirements for specialized components. The result of these analyses are described briefly in the following paragraphs.

SSSD Multiplexing Approach - This approach appears to be the most attractive from the standpoint of reduced component count within the EOA. However, this reduced component count is usually offset by a corresponding increase in EOA complexity. Many of the SSSD approaches require specialized components which make these devices difficult to implement. Three types of SSSD multiplexing approaches were evaluated: optical switch, passive splitter, and linear tapped bus.

An example of an **optical switch** based approach is shown if Figure 3-13.



ELECTRO-OPTIC SWITCH:

- Low Speed/Low Power Optical Source
- Requires Single Mode Fiber Optics
- Optical Switching Speed < 1 Nanosecond
- Supports Greatest Number of Sensors (N)

MECHANICAL SWITCH:

- Low Speed/Low Power Optical Source
- Compatible with Multimode Fiber Optics
- Mechanical Switching Speed > 5 Milliseconds
- Supports 5 Sensors Max at 40 Hz Update

MULTIPLEXING LOSSES (N = 10):

Connectors:	4 Connectors
	x 2.0 dB/Connector
	8.0 dB
Optic Switch:	2.0 dB Insertion loss
10 : 1 Coupler:	3.0 dB Insertion loss

$\boxed{\text{Multiplexing Losses: 13.0 dB}}$

LOSS BUDGET ANALYSIS:

Minimum Interconnect Loss:	16.0 dB
Minimum Safety Margin:	15.0 dB
Multiplexing Losses:	13.0 dB
Minimum Loss Budget:	**44.0 dB**

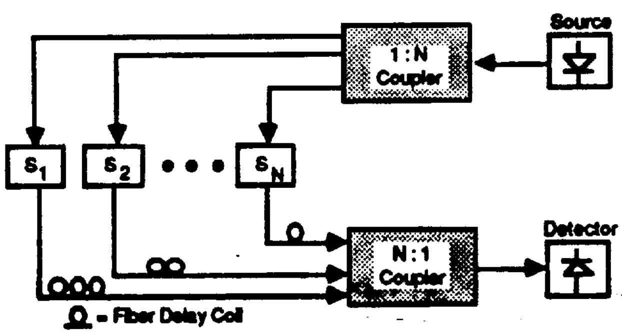
Figure 3-13 Optical Switch Multiplexing Approach

The two types of optical switches that were evaluated for this approach were found to be unacceptable for aircraft multiplexed flight control applications.

Electro-Optic Switch - This switch operates on the principle of a voltage induced refractive index change to switch the optical path. Since switching speed is only limited by the capacitance of the switching electrode, these devices can be switched extremely fast (< 1ns) and are thus useful for multiplexing a large number of sensors. The major drawback of these devices is that they are currently only compatible with single mode optical sources and are not yet widely available.

Opto-Mechanical Switch - This switch operates on the principle of electro-mechanical movement of a precisely aligned fiber array (moving fiber type) or an optical prism (beam deflection type). Both of these devices are compatible with multimode fiber optic sensors. These devices typically have very slow switching speeds (> 5ms) and are therefore not desirable for multiplexed applications. Another drawback of these devices is that they are unreliable as compared to equivalent solid state devices, and they are usually sensitive to vibration.

An example of an **passive splitter** based approach is shown if Figure 3-14.



TDM/PASSIVE OPTIC COUPLER:

- Requires High Speed/High Power Source
- Compatible with Multimode Fiber Optics
- Supports Limited Number of Sensors (Determined by Optical Power Budget)

MULTIPLEXING LOSSES (N = 10):

Connectors:	4	Connectors
	x 2.0	dB/Connector
	8.0	dB
10 x 10 Coupler:	10.0	dB Splitting Loss
	+ 2.0	dB Excess Loss
	12.0	dB
10 : 1 Coupler:	3.0	dB Insertion Loss

Multiplexing Losses: 23.0 dB per channel

LOSS BUDGET ANALYSIS (per channel):

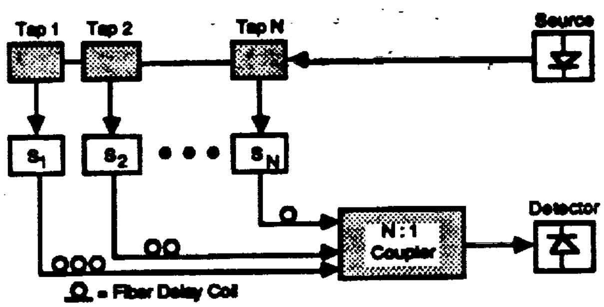
- Minimum Interconnect Loss: 16.0 dB
- Minimum Safety Margin: 15.0 dB
- Multiplexing Losses: 23.0 dB

Minimum Loss Budget: 54.0 dB

Figure 3-14 Passive Splitter Multiplexing Approach

The passive splitter approach to multiplexing appears to be quite attractive from the EOA standpoint. However, there are several drawbacks to this approach. First, the EOA must contain a very high power optical source to overcome the physical splitting loss (10 Log N) associated with the passive coupler. The limited optical power budget available will tend to limit the number of sensors that can be effectively multiplexed. Another drawback is that the EOA requires a very high speed (100 MHz) pulsed optical source to minimize the size of the fiber time delay coils required for each sensor. The location of these time delay coils within the aircraft also presents a formidable problem since each coil is unique. If these coils are located within the sensor itself, then the sensor becomes a unique element and aircraft spares are difficult to control effectively. Likewise, the coils cannot be located within the fiber link connecting the sensor to the EOA due to cabling restrictions within the aircraft. The only acceptable location for these coils would be within the EOA itself.

An example of a **linear tapped bus** approach is shown in Figure 3-15.



TDM/LINEAR TAPPED BUS:

- Requires High Speed/High Power Source
- Compatible with Multimode Fiber Optics
- Supports Limited Number of Sensors (Determined by Optical Power Budget)

MULTIPLEXING LOSSES (N = 10):

Connectors:	22	Connectors (1)
	x 2.0	dB/Connector
	44.0	dB
10 : 1 Coupler:	3.0 dB	Insertion Loss
Multiplexing Losses: 47.0 dB		

LOSS BUDGET ANALYSIS:

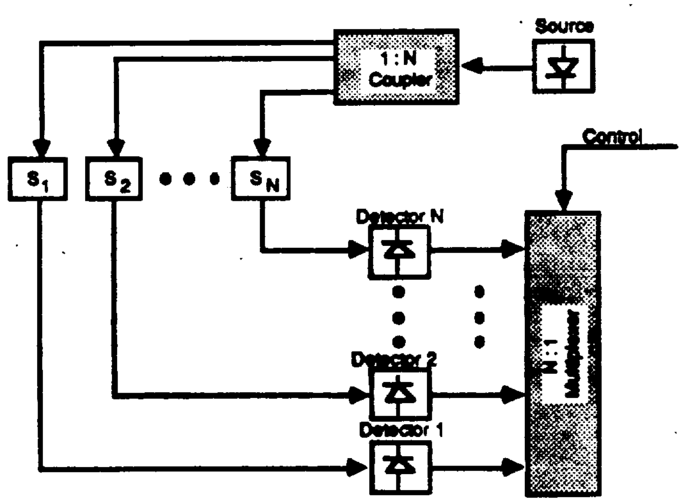
Minimum Interconnect Loss:	16.0 dB
Minimum Safety Margin:	15.0 dB
Multiplexing Losses:	47.0 dB
Minimum Loss Budget:	**78.0 dB**

(1) Assume 10 Taps, Each With 2 Connectors in the Signal Path (Plus 2 Connectors for 10:1 Coupler)

Figure 3-15 Linear Tapped Bus Multiplexing Approach

The linear tapped bus is a variation of the passive splitter approach with the splitters distributed throughout the aircraft. On the surface, this approach appears to be the most attractive from the standpoint of reduced EOA component count and reduced fiber count. The linear tapped bus approach was the most popular multiplexing approach among the vendors surveyed for the optical sensor data base. As can be seen in the loss budget of Figure 3-15, this approach is extremely difficult to implement in a production aircraft environment. To provide the required level of aircraft maintainability, the individual taps must be treated as line replaceable units and will therefore require individual fiber optic connectors. The optical power budget required to overcome the losses associated with this excessive number of connectors precludes consideration of the linear tapped bus for aircraft applications. This problem is intensified in those systems where the return fiber is also a tapped bus.

SSMD Multiplexing Approach - This multiplexing approach is similar to the SSSD passive splitter approach in that the power from a single optical source is divided equally among all of the sensors. However this approach relies on individual detectors dedicated to each sensor channel. Returned optical signals are time division multiplexed electronically at the receiver by addressing the appropriate detector channel. This configuration will generally have a higher sensitivity than the SSSD approach due to the reduced bandwidth requirements of the individual detector channels. A drawback to this approach is the requirement for a high power optical source to overcome the physical splitting loss associated with the passive coupler. The limited optical power budget available will tend to limit the number of sensors that can be effectively multiplexed. Another drawback is the requirement for a separate detector dedicated to each sensor. Since the EOA detector is typically much more complicated than the transmitter for most sensor applications, this technique will tend to increase the overall EOA complexity. An example of the SSMD multiplexing approach is shown in Figure 3-16.



FEATURES:

- Requires High Power Optical Source
- Compatible with Multimode Fiber Optics
- Requires One Detector for Each Sensor (Not Desireable for APD Based Applications)
- Supports Limited Number of Sensors (Determined by Optical Power Budget)

MULTIPLEXING LOSSES (N = 10):

Connectors:	2	Connectors
	x 2.0	dB/Connector
	4.0	dB
1 x 10	10.0	dB Splitting Loss
Coupler:	+ 2.0	dB Excess Loss
	12.0	dB

Multiplexing Losses: 16.0 dB

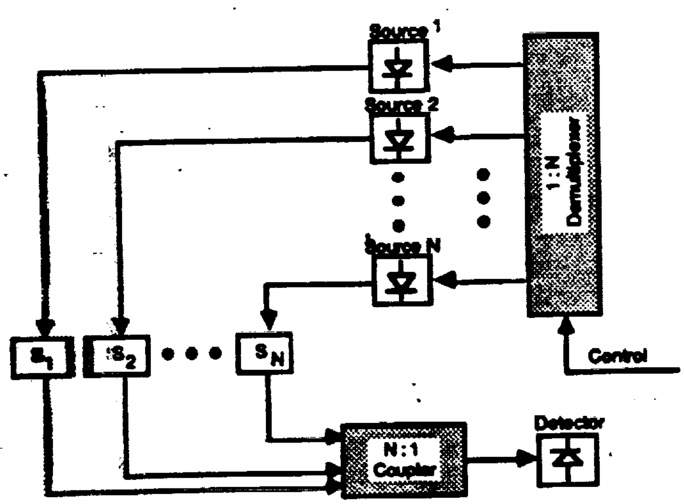
LOSS BUDGET ANALYSIS:

- Minimum Interconnect Loss: 16.0 dB
- Minimum Safety Margin: 15.0 dB
- Multiplexing Losses: 16.0 dB

Minimum Loss Budget: 47.0 dB

Figure 3-16 SSMD Multiplexing Approach

MSSD Multiplexing Approach - This multiplexing approach requires one optical source dedicated to each sensor channel. The EOA receiver can be time division multiplexed by merely addressing the appropriate sensor from the transmit side. Network losses are minimized since the full power of an individual optical source is available to each sensor being multiplexed. Because of the low network losses associated with this configuration, it is possible to construct the EOAs from relatively simple low speed/low power multimode optical components. Furthermore, it may be possible to further reduce the multiplexing losses by eliminating the passive coupler on the receiver channel. If the number of multiplexed sensors is small, it may be possible to construct a non-reciprocal power combiner by combining all of the sensor receive fibers into a single fiber bundle. This approach eliminates the physical splitting losses (10 log N) and excess losses associated with a fused biconical type reciprocal power combiner. Anticipated losses for this type of multiplexing will depend on the number of receive fibers and the surface area of the receiver photodetector, but can generally be assumed to be less than 3 dB. Although this power combiner can be considered to be a somewhat "specialized" component, it is fairly easily constructed. This approach is acceptable from a maintainability and integrated logistics support viewpoint since the combiner is confined to the EOA module itself. For the reasons of simplicity, flexibility, and low optical losses, this multiplexing approach was determined to be optimal for the greatest number of sensing applications and is therefore the preferred multiplexing approach for EOAs. An example of the MSSD multiplexing approach is shown in Figure 3-17.



FEATURES:

- Low Speed/Low Power Optical Sources
- Compatible with Multimode Fiber Optics
- Requires One Source for Each Sensor (Not Desireable for Laser Based Applications)
- Supports Large Number of Sensors (Limited by Multiplexing Electronics)

MULTIPLEXING LOSSES (N = 10):

Connectors:	2	Connectors
	x 2.0	dB/Connector
	4.0	dB
10 : 1 Coupler:	3.0 dB	Insertion loss
Multiplexing Losses:	**7.0 dB**	

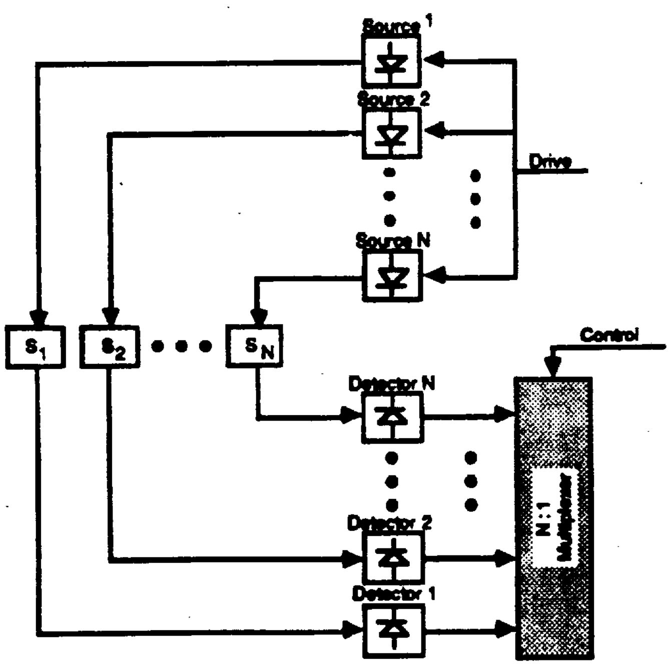
LOSS BUDGET ANALYSIS:

- Minimum Interconnect Loss: 16.0 dB
- Minimum Safety Margin: 15.0 dB
- Multiplexing Losses: 7.0 dB

Minimum Loss Budget: 38.0 dB

Figure 3-17 MSSD Multiplexing Approach

MSMD Multiplexing Approach - This multiplexing approach requires one source and one detector dedicated to each sensor. Each of the sources continuously illuminate their respective sensor. The returned optical signals are time division multiplexed electronically at the EOA receiver. Since there are no optical multiplexing losses associated with this network approach, it can support a large number of optical sensors. Additionally, the EOA can be constructed out of relatively simple low speed/low power multimode optical components. The main drawback of this approach is the requirement for a separate detector dedicated to each sensor. Since the EOA detector is typically much more complicated than the transmitter for most sensor applications, this technique will tend to increase the overall EOA complexity. An example of the MSMD multiplexing approach is shown in Figure 3-18.



FEATURES:

- Low Speed/Low Power Optical Sources
- Compatible with Multimode Fiber Optics
- Requires Source and Detector for Each Sensor (Not Desireable for Laser Based Applications)
- Supports Large Number of Sensors (Limited by Multiplexing Electronics)

LOSS BUDGET ANALYSIS:

- Minimum Interconnect Loss: 16.0 dB
- Minimum Safety Margin: 15.0 dB
- Multiplexing Losses: 0.0 dB

No Optical Multiplexing Losses (N = 10): $\Sigma\Rightarrow$

Minimum Loss Budget:	31.0 dB

Figure 3-18 MSMD Multiplexing Approach

EOA designs were completed for all of the candidate optical sensor technologies exhibiting potential for aircraft flight control and air data sensor applications. The following EOA designs were completed under this task:

- **OTDR Backscatter**
- **PBL Remote Electrical** (laser based)
- **PBL Remote Electrical** (LED Based)
- **TDIN Gradient Filter Plate**
- **TDIN Absorption Edge Shift** (same as TDIN Filter Plate)
- **TDIN Microbend Modulated** (same as TDIN Filter Plate)
- **TDM Beam Interrupt**
- **TDM Optical Code Plate**
- **TRD Fluorescent**
- **TRD Phosphorescent**
- **WDIN Absorption Edge Shift**
- **WDIN Fabry-Perot Interferometer**
- **WDIN Gradient Filter Plate**
- **WDIN Microbend Modulated**
- **WDIN Photo-Elastic**
- **WDIN Reflective Diaphragm**
- **WDM Fabry-Perot Interferometer**
- **WDM Optical Code Plate** (Bulb based)
- **WDM Optical Code Plate** (LED Array)
- **WDM Diffraction Grating** (same as WDM Code Plate)
- **WDM Photo-Elastic** (same as WDM Code Plate)

Detailed designs for these EOAs are included in Appendix B. Each EOA design was based upon detailed information from representative sensor manufacturers concerning optical modulation/demodulation requirements for implementation of each candidate sensor technology. Several of the candidate optical sensor technologies investigated warranted the design of multiple EOAs in order to analyze unique implementations between the various sensor manufacturers. Each EOA utilizes an optimized multiplexing scheme based on the optical power budget available. Because the approach to power budget analysis and management can very greatly between manufacturers, the candidate EOAs in Appendix B may not be representative of each manufacturer's "preferred" implementation approach. For this reason, the manufacturers have not been referred to by name.

3.1.6 Task 1.6 Develop MCAIR Architecture Evaluation Criteria & Weighting Factors

This task developed suitable architecture evaluation criteria to allow a comprehensive comparison between the candidate EOAs designed under Task 1.5. This evaluation criteria included such issues such as reliability, maintainability, redundancy, cost/weight/volume, environment, and optical power budget. Relative weighting factors were assigned to the evaluation criteria to allow comparisons between various EOAs. These evaluation criteria and relative weighting factors were submitted to NASA for approval prior to proceeding to Task 1.7.

In the process of defining suitable architecture evaluation criteria, it became apparent that the scope of this effort would have to be expanded in order to perform a comprehensive and accurate evaluation of the candidate architectures. Each of the EOAs developed under Task 1.5 was evaluated against the key evaluation criteria for avionics architectures as defined under the Air Force's High Reliability (HI-REL) Fighter study. In order to adequately understand these criteria, it is first necessary to define each criteria in clear-cut, unambiguous terms. Once this has been accomplished, it is possible to describe the relationship between these criteria and to assign relative weighting factors to each.

The key evaluation criterion, according to the HI-REL fighter study, was determined to be supportability. Supportability is composed of three key elements: reliability, maintainability, and Integrated Logistics Support (ILS). Priorities were established with respect to each of these elements of supportability. Top priority was given to reliability because it drives the other elements. For example, a reduction in the number of parts in an EOA leads to improved reliability. This in turn means reduced maintenance actions (a maintenance improvement) and reduction in the number of required spares (an ILS improvement). Examples of key reliability features include designing for the environment, parts reduction, component quality improvement, etc. Key maintainability features that do not require improved reliability include reduced access time, improved fault isolation, diagnostics and built-in test, etc. Likewise, significant ILS features include increased spares protection level, decreased manning levels, etc. As a whole, each element of supportability offers independent enhancements, but only reliability offers features that drive other elements.

The HI-REL fighter study defined five Measures of Merit (MoM) upon which architecture evaluation should be based. The five MoM determinants, include downtime, Life Cycle Cost (LCC), mission capable rate, sortie rate, and deployability. A study of the interrelationships among these five determinants revealed that downtime was the single most important figure of merit contributing to weapons system readiness. Downtime per flight hour combines each of the elements of supportability (redundancy, maintainability, and integrated logistics support) and normalizes them to flight hours. Downtime consists of elapsed maintenance time (EMT), awaiting maintenance time (AWM), and awaiting parts time (AWP). Values for EMT, AWM, and AWP were derived from the MoM computer modeling program.

The EOA Configuration Development and Evaluation plan as originally conceived is shown in Figure 3-19.

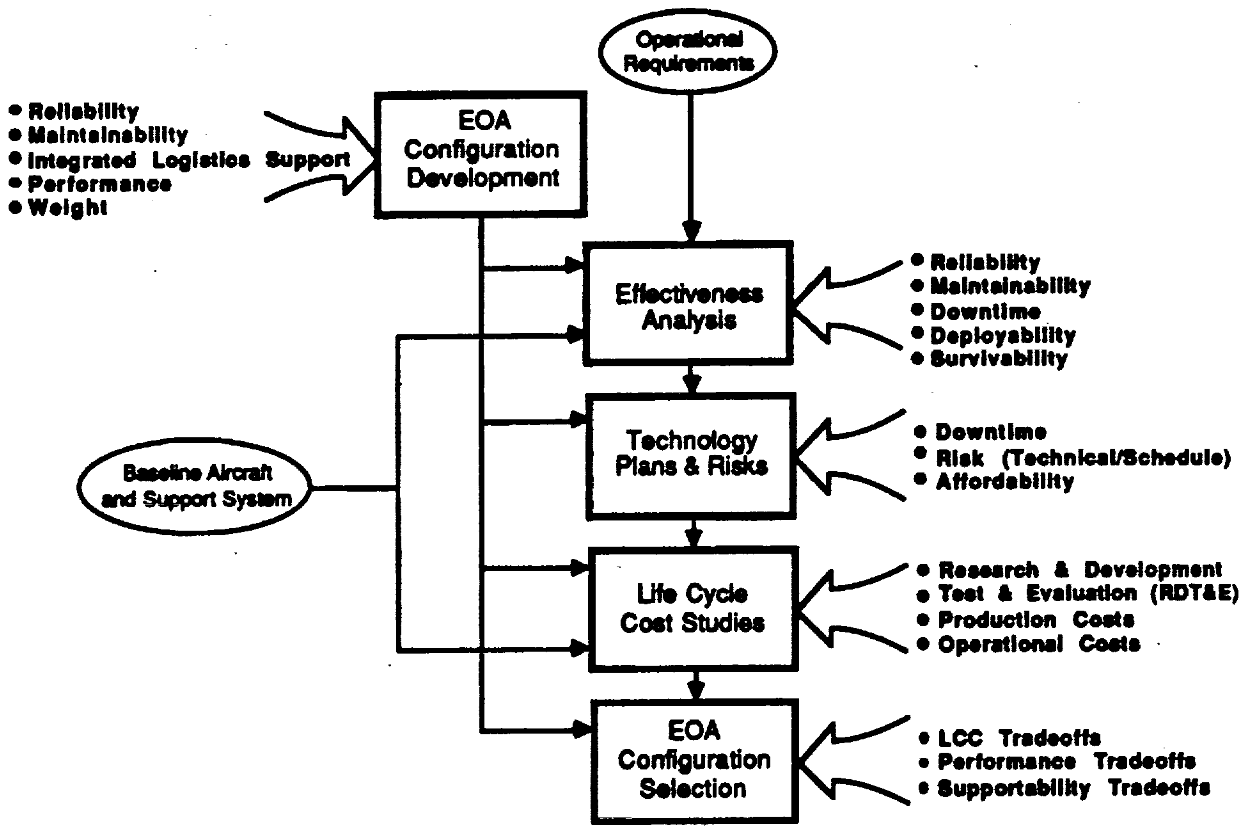


Figure 3-19 EOA Configuration Development and Evaluation

The EOA Configuration Development and Evaluation Plan would ideally include the following five phases in the architecture evaluation process:

Phase I: EOA Configuration Development - Evaluate the supportability characteristics (reliability, maintainability, and integrated logistics support) of the candidate EOAs.

Phase II: Effectiveness Analysis - Evaluate the effectiveness of the candidate EOAs and associated support equipment with regard to a given operational scenario. The EOAs and support systems should be evaluated in terms of supportability, downtime, availability, and deployability. A campaign analysis would then be performed to determine expected kills, sortie rates, and loss rates against a baseline aircraft architecture.

Phase III: Technology Plans & Risks - Evaluate candidate EOAs to determine the most promising technologies based upon downtime reduction, technical risk, and affordability. A qualitative sensitivity analysis would then be performed in order to assess performance, weight, cost, resources, and risk associated with each of the candidate EOAs under consideration.

Phase IV: Life Cycle Cost Studies - Estimate life cycle costs for each of the candidate EOAs. Major cost drivers for each EOA will be identified in this phase. Data collected to make these estimates would include a detailed weights breakout by subsystem, material distribution, and estimated complexity.

Phase V: EOA Configuration Selection - Determine the "preferred" sensor modulation technique and associated EOA based upon the evaluation criteria.

Throughout the EOA evaluation process, trade-offs between life cycle costs, performance, and supportability must be conducted in order to arrive at an "optimum" architecture which is a blend of the best possible supportability characteristics given performance, affordability, and survivability constraints.

3.1.7 Task 1.7 - Evaluate Candidate Sensor/EOA Combinations

This task evaluated the candidate EOAs against the evaluation criteria and relative weighting factors in order to identify the optimal EOA configuration. The results of these analyses indicated that of the three key evaluation criteria (reliability, maintainability, and integrated logistics support) which determine overall system supportability and aircraft downtime, system reliability was the overriding factor in the selection of the optimal EOA configuration. This was largely due to the lack of available data on maintenance and ILS requirements for architectures based on this emerging technology. Because of the lack of available data, maintainability was a secondary consideration followed closely by ILS.

EOA reliability data was based on MIL-STD-217E analyses with regard to the following assumptions:

- An aircraft Initial Operational Capability (IOC) date of 1995 was assumed. This IOC date effectively set a technology cutoff date in the early 1990's. This tended to increase the reliability estimates for those EOAs employing emerging technologies which are projected to increase in reliability in the future. For example, the reliability of the WDM Digital Optical Code Plate architecture was projected to be 62,734 hours. This is approximately three times the manufacturer's reliability estimate (20,000 hours) for a present day technology implementation of the equivalent architecture. The reliability increase can be largely attributed to the projected increases in reliability of the charge coupled device used in the WDM receiver circuit.

- Reliability figures were based upon Mean Flight Hours Between Failures (MFHBF) and not Mean Time Between Failures (MTBF). The MFHBF reliability number provides the best indicator of overall aircraft availability. Since MFHBF does not include the time that the aircraft is on the ground but powered up (i.e. warm up and taxi), this number will tend to be somewhat lower than the MTBF reliability figures typically quoted by the EOA manufacturers.

- Reliability of the optical sensor and associated optical interconnect could not be included in the overall EOA analysis due to lack of environmental performance data for these components. As a result, EOA reliability estimates may not agree with projected estimates by the sensor manufacturers.

EOA reliability was selected to be the discriminating factor in the selection of an "optimal" EOA configuration. Reliability estimates for both non-multiplexed (single sensor) and multiplexed (multiple sensors) EOA configurations were calculated. The multiplexed EOA configurations were based upon actual aircraft requirements for number of sensors. By comparing the reliability ratios between these two configurations is was possible to determine which sensor technologies were best suited to multiplexing. By comparing the overall reliability figures for the multiplexed EOAs it was possible to identify an "optimal" sensor technology. EOA reliability results are presented in Figures 3-20 through 3-22.

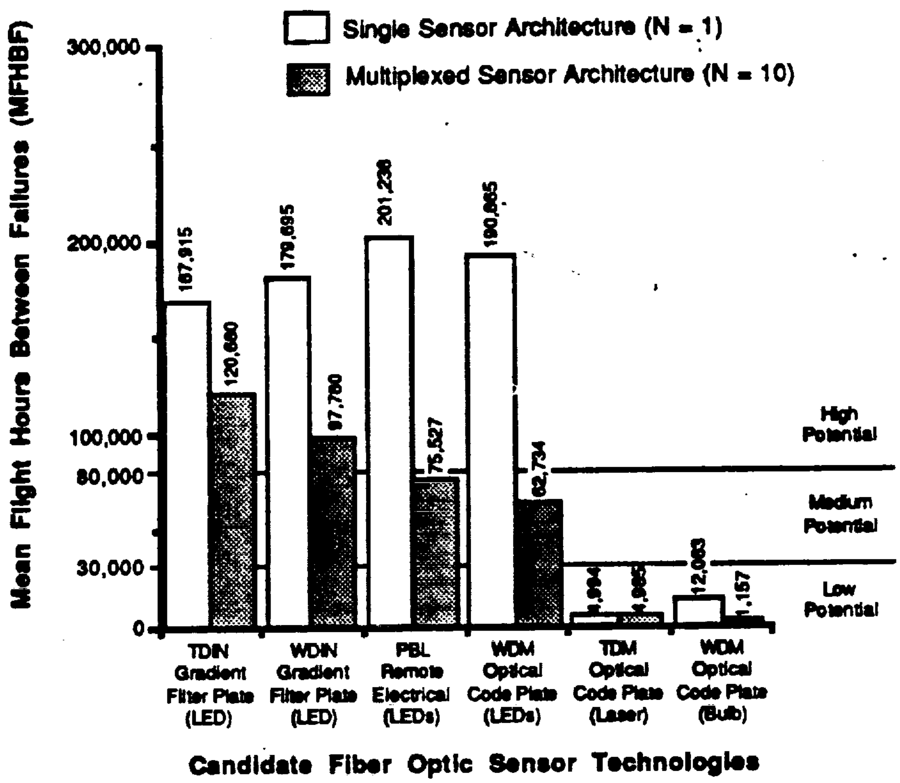


Figure 3-20 EOA Reliability Analysis (Linear/Rotary Position Sensor)

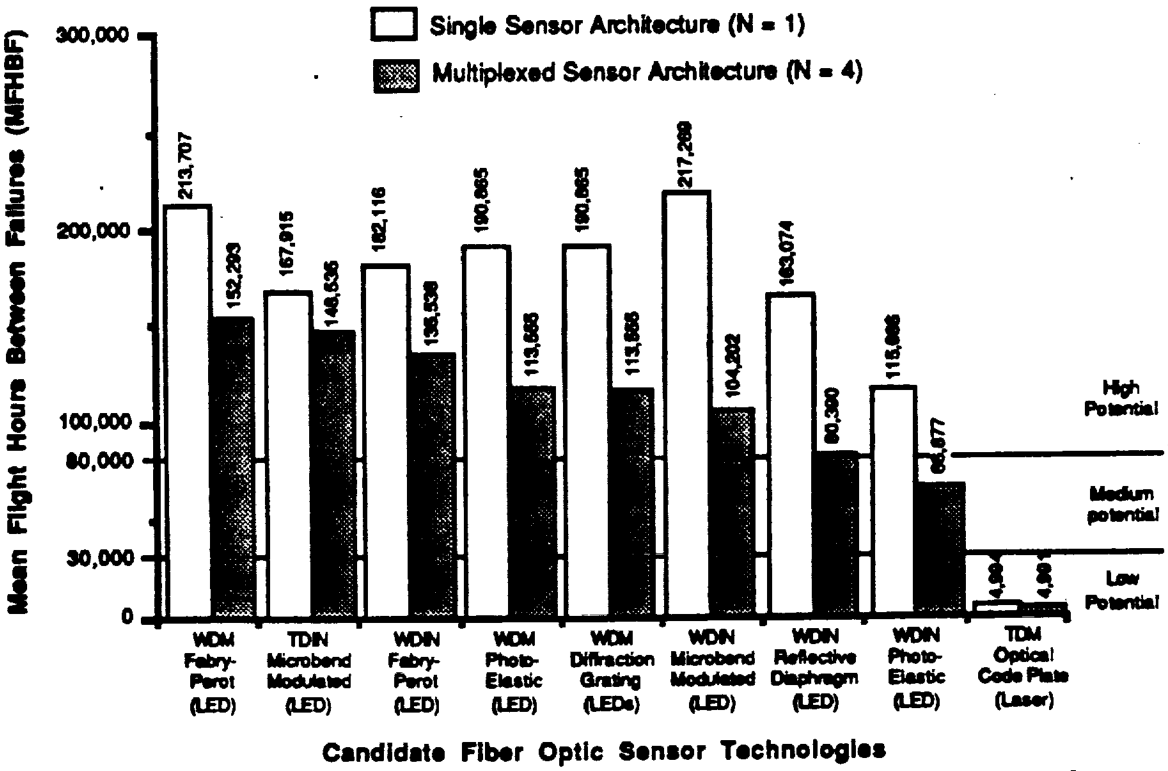


Figure 3-21 EOA Reliability Analysis (Pressure Sensor)

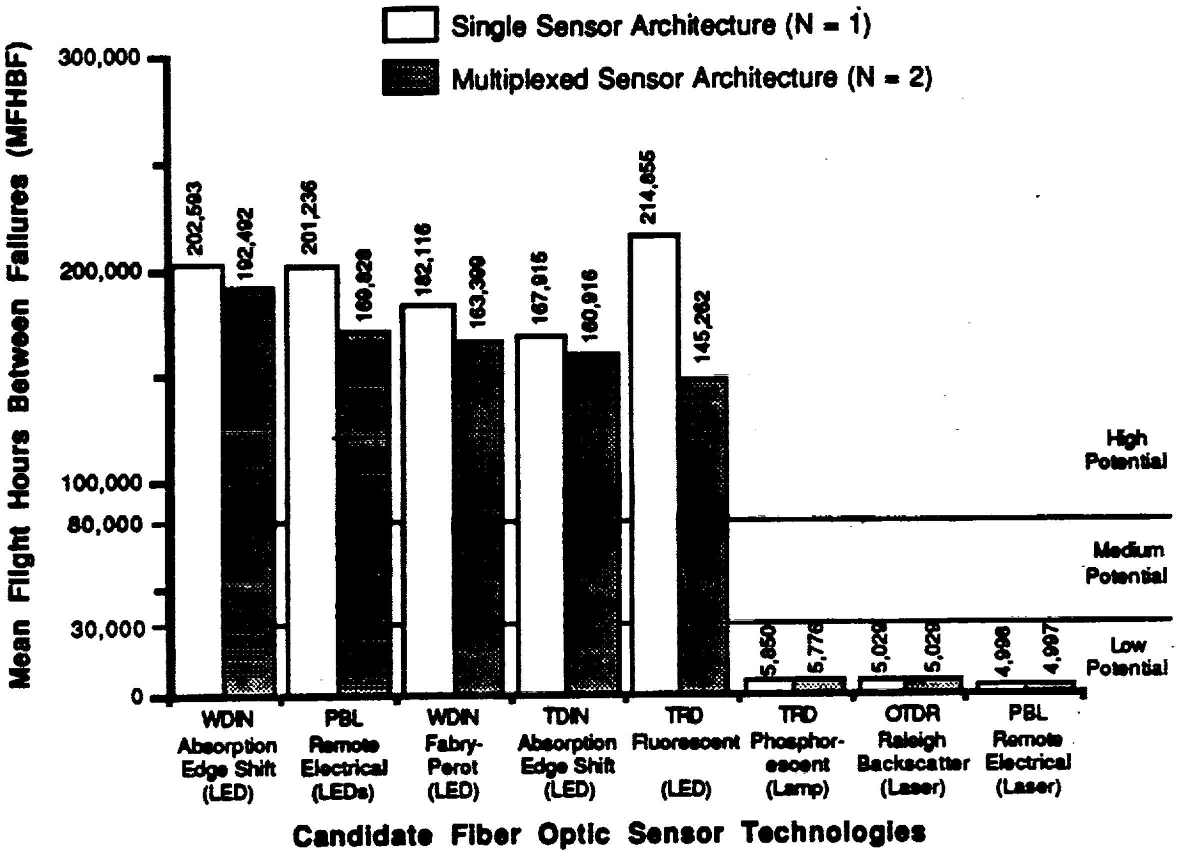


Figure 3-22 EOA Reliability Analysis (Temperature Sensor)

A comparison of the overall reliability figures for multiplexed EOAs revealed that it was not possible to select an "optimal" EOA configuration using reliability as the sole discriminator. A more accurate evaluation must therefore include three elements of supportability as the discriminator: (1) reliability, (2) maintainability, and (3) ILS. However, the lack of available data on maintenance and ILS requirements for this relatively immature technology precludes their use as viable discriminators at this time. Using reliability as a preliminary discriminator, however, it is possible to identify several "preferred" sensor technologies. The EOA conceptual design efforts previously planned under Task 2 were subsequently modified to include several EOAs to accommodate this entire range of "preferred" sensor technologies.

3.1.8 Task 1.8 - Recommend Preferred Sensor Modulation Techniques and Associated EOAs

This task made specific recommendations as to which sensor optical modulation techniques and associated EOAs are desirable for advanced aircraft. The results of the analyses conducted under Task 1.7 were used to select an optimal EOA configuration for each category of aircraft flight control and air data sensor. The results of Task 1 evaluation efforts indicate two points: (1) no singular optical sensor technology can be optimized for all aircraft sensor applications, and (2) no strong discriminator exists upon which to base the selection of an "optimal" EOA technology for any given sensor application. It is possible, however, to recommend several "preferred" optical sensor technologies based upon the results of Task 1. A composite chart outlining these preferred technologies is presented in Figure 3-23.

CANDIDATE FIBER OPTIC SENSORS			POTENTIAL		
TYPE	TECHNOLOGY	REFERENCE	LOW	MED	HIGH
Linear Accelerometer	Microbend Modulated	WDIN			LED
	Mach-Zehnder Interferometer	FMCW	Laser		
Rate Gryoscope	Sagnac Interferometer	FMCW			Laser
Linear/Rotary Position (N=10)	Digital Optical Code Plate	TDM	Laser		
		WDM	Bulb	LEDs	
	Analog Gradient Filter Plate	TDIN			LED
		WDIN			LED
	Beam Interrupt/Pulse Count	TDM	N/A		
	Power-By-Light (PBL)	LEDs		LEDs	
Pressure (N=4)	Digital Optical Code Plate	TDM	Laser		
	Microbend Modulated	TDIN			LED
		WDIN			LED
	Reflective Diaphragm	WDIN			LED
	Fabry-Perot Interferometer	WDIN			LED
		WDM			LED
	Moving Diffraction Grating	WDM			LEDs
	Michelson Interferometer	FMCW	Laser		
	Photo-Elastic	WDIN		LED	
		WDM			LED
Speed	Beam Interrupt/Pulse Count	TDM			LED
Temperature (N=2)	Absorption Edge Shift	TDIN			LED
		WDIN			LED
	Raman/Raleigh Backscatter	OTDR	Laser		
	Blackbody Radiation	SELF	N/A		
	Passive IR Analysis	SELF	N/A		
	Fabry-Perot Interferometer	WDIN			LED
	Phosphorescent	TRD	Lamp		
	Fluorescent	TRD			LED
	Sagnac Interferometer	FMCW	Laser		
	Power-By-Light (PBL)	LEDs/Laser	Laser		LEDs

NOTE: Numbers in parentheses indicate the number of sensors multiplexed by a single EOA

Figure 3-23 Preferred Fiber Optic Sensor Technologies

3.2 Task 2.0 - <u>DETAILED DESIGN</u>

This task involved the development of Level 1 conceptual designs for an aircraft integrated EOA system. The preferred sensor modulation technologies and associated EOAs identified under Task 1 were used as a starting point for this process. By identifying and exploiting the functional commonalties that exist among the preferred sensors , it was possible to develop a minimal set of EOA Level 1 hardware designs to accommodate the entire range of preferred sensors. Part of this design process involved the identification of critical component technologies required to construct an all optical aircraft flight control system. Interface specifications were then developed for each of the candidate EOA designs in order to ensure compatibility with the preferred sensors technologies. Interconnection of the EOAs to the sensors, actuators, and flight controllers was addressed, and a conceptual design for an aircraft integrated EOA system was proposed. The manner in which the candidate EOAs could be integrated into an advanced aircraft VMS architecture was also addressed. Task 2 was composed of six subtasks as outlined in the roadmap of Figure 3-24.

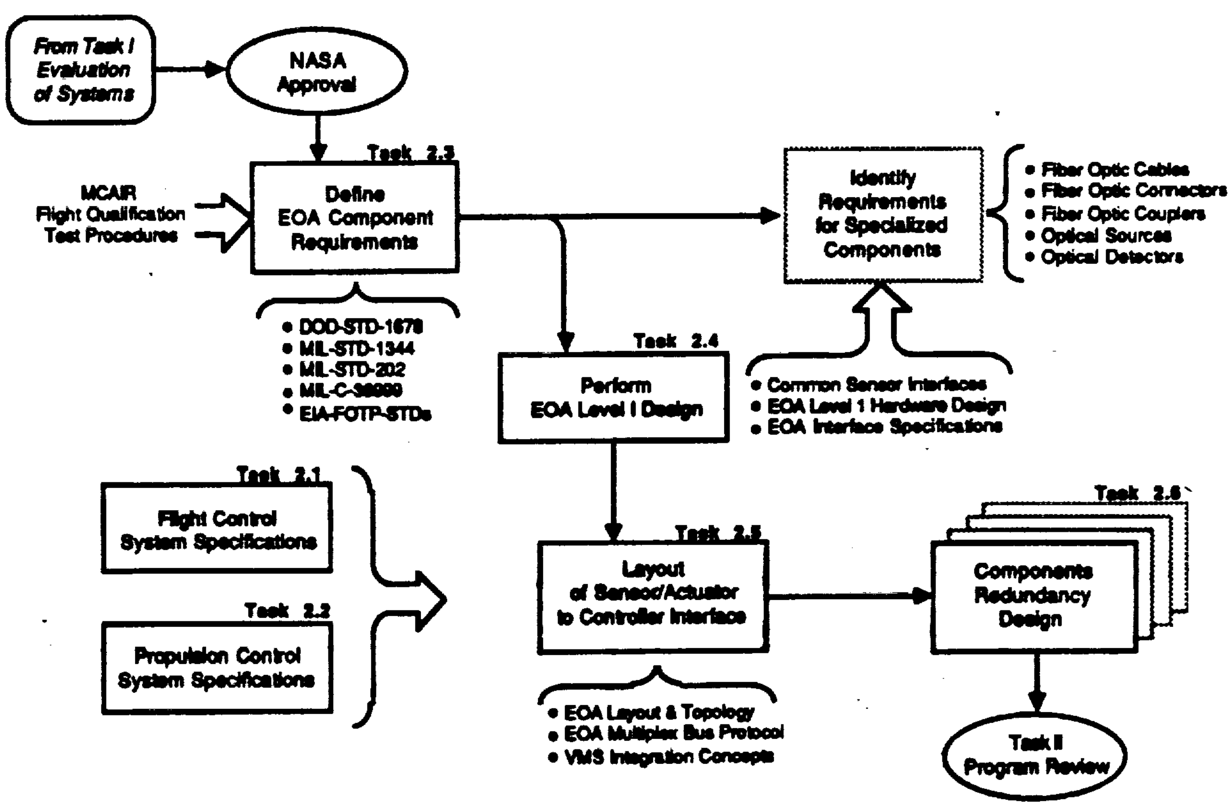


Figure 3-24 Task 2 Roadmap

3.2.1 Task 2.1 - Flight Control Systems Specifications

This task defined the system level requirements for the flight control and air data systems. The F-15/SMTD aircraft was selected as the point design for this task. Flight control and air data system level requirements were defined in the areas of data latency, fault tolerance, and redundancy. As with the individual EOAs, system supportability was a prime consideration in the development of the Level 1 system architecture. Since this task is dependent on the physical layout of the sensors and EOA to the airframe, it was decided to address these issues under Tasks 2.5 and 2.6.

3.2.2 Task 2.2 - Propulsion Control System Specifications

This task defined the system level requirements for aircraft propulsion control. Once again, the F-15/SMTD was used as the point design for this process. Flight control and air data system level requirements were defined in the areas of data latency, fault tolerance, and redundancy. Since this task is dependent on the physical layout of the sensors and EOA to the airframe, it was decided to address these issues under Tasks 2.5 and 2.6.

3.2.3 Task 2.3 - Define EOA Component Requirements

This task specified the components required to construct an EOA system. Before beginning the detailed Level 1 EOA designs under Task 2.4, it was first necessary to define the operational and environmental performance requirements for the individual optical components required to construct an EOA system. These components include optical fiber, connectors, and couplers. Wherever appropriate, MCAIR flight qualified optical components were specified. The standard tests that these passive optical components must undergo in order to become flight qualified by MCAIR are included in Appendix C. The test conditions outlined in these charts are representative of the actual aircraft environments experienced by these components. To pass flight qualification testing, these components must be capable of withstanding thermal environments ranging from -65 degrees to +200 degrees Celsius and mechanical shock levels of up to 300 G's in any axis.

Fiber Requirements - The fiber optic cable used to interconnect the sensors to the EOAs must provide reliable, low loss operation over a wide range of environmental extremes. All types of optical fiber which have been previously flight qualified at MCAIR have a 100/140 micron core/cladding ratio. Attempts to qualify a 200 micron core optical fiber have been unsuccessful due to fiber breakage during mandrel wrap testing. Recently introduced 200 micron hard clad silica fibers have successfully passed the mandrel wrap test but have subsequently failed during temperature cycling due to inherent thermal limitations of the fiber polymer coating.

MCAIR currently has two flight qualified fiber optic cables. Both cables are of graded index construction. The first is a fluorine doped fiber rated for 150 degrees Celsius operation, and the other is a phosphor doped fiber rated for 200 degrees Celsius operation. The latter fiber is polyimide coated to reduce overall cable size and weight. This cable is only 0.083 inches in diameter and weighs only 4.0 pounds per thousand feet. An example this cable is shown in Figure 3-25.

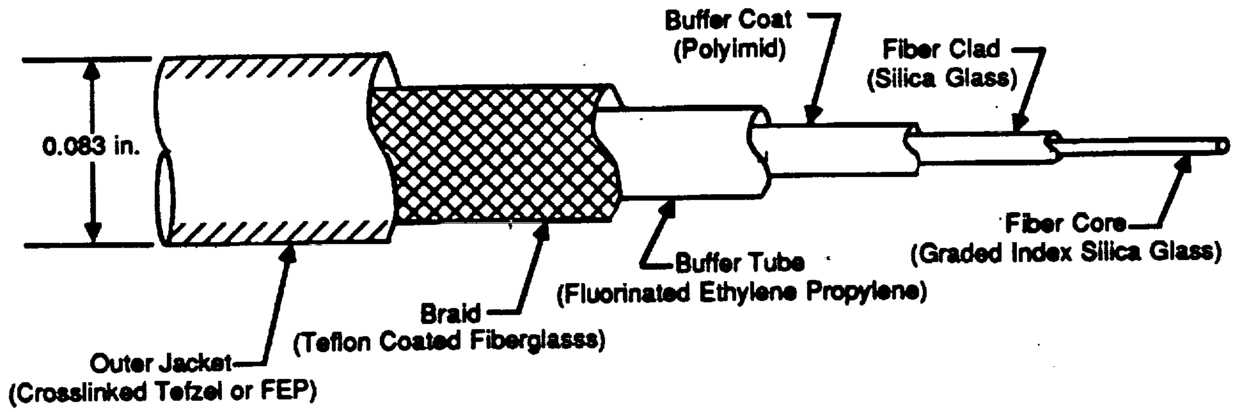


Figure 3-25 Graded Index Fiber Optic Cable

Graded-index fibers traditionally have very low optical dispersion characteristics resulting in very high data bandwidths. Because of these characteristics, graded-index fibers were a natural selection for use on high speed airborne fiber optic links. While a graded-index fiber is desirable for high speed data communications, it may present a problem when applied to EOAs employing wavelength referenced sensors. Certain doping materials used in the manufacture of graded-index fibers may tend to act as a temperature dependent absorption edge shift sensors resulting in high attenuation at for some wavelengths and temperatures. Until additional spectral evaluation of graded-index fiber is completed, it would be prudent to specify step-index fiber for wavelength referenced EOAs.

Connector Requirements - To maintain compatibility with existing aircraft electrical interconnects, the sensor/EOA interface must contain MIL-C-38999 compatible, size 16 single fiber termini. Although many fiber optic cables exist for +200 degrees Celsius operation, most 38999 compatible connectors are currently limited to +150 degrees Celsius operation due to thermal breakdown of the epoxy used to encapsulate the fibers. In order to achieve operation at +200 degrees Celsius, a reliable epoxy-less (crimp /cleave) type connector should be used. To reduce aircraft repair time and maintenance personnel skill levels, a non-polish type of quick termination is desirable. However, previous attempts to flight qualify a dry/non-polish connector were largely unsuccessful due to unacceptable loss characteristics. An example of a MIL-C-38999 compatible connector is shown in Figure 3-26.

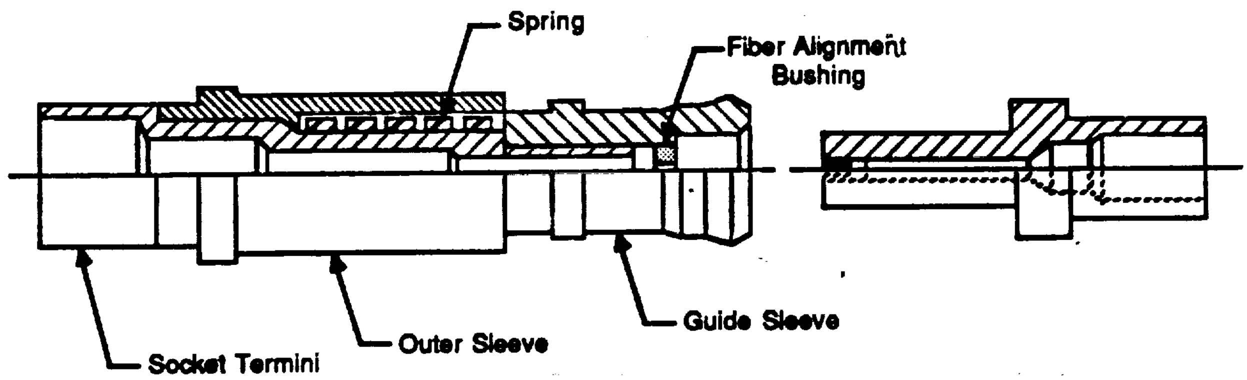


Figure 3-26 MIL-C-38999 Fiber Optic Connector

Coupler Requirements - Two types of passive couplers are currently available: fused biconical taper, or integrated optic. The fused biconical type coupler is manufactured by twisting the fibers together and heating the junction to form a mixing region for the optical signal. Because of non-uniformities in this mixing region, these devices typically exhibit undesirable sensitivities to modal distribution, vibration, and humidity. A relatively new type of optical coupler is the integrated optic or planar waveguide type coupler. These devices are constructed by etching optical waveguides directly into a substrate using standard semiconductor photo-resist fabrication techniques. This manufacturing precision provides for a very controlled coupling efficiency and insensitivity to modal dependencies. Because of the power budget penalties associated with any passive coupler, these devices are generally not desirable. Although these devices are not currently required for construction of the EOA, they will be required for certain sensors (WDM, TDM, and PBL). An example of an innovative planar waveguide coupler is shown in Figure 3-27.

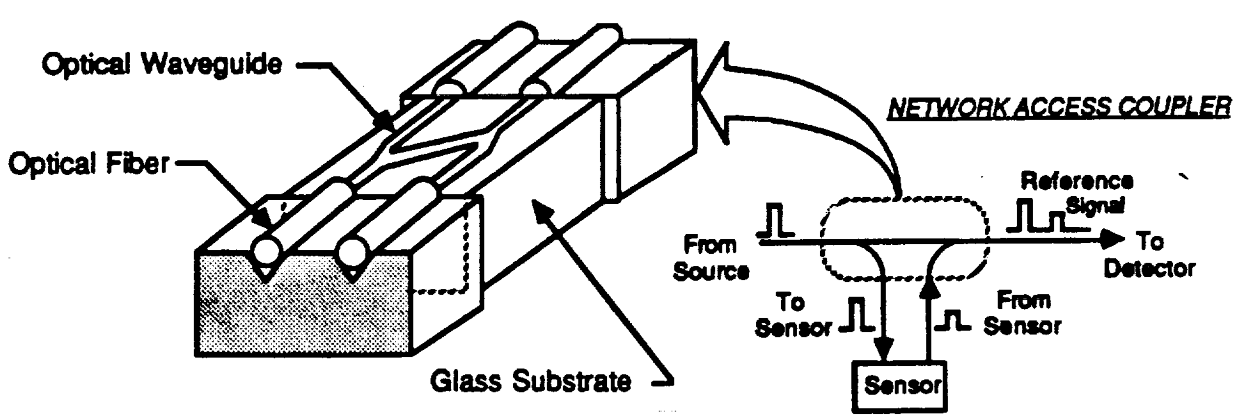


Figure 3-27 Planar Waveguide Fiber Optic Coupler

3.2.4 Task 2.4 - Perform EOA Level 1 Design

This task involved the development of Level 1 conceptual designs for an aircraft integrated EOA system. The preferred sensor modulation technologies and associated EOAs identified under Task 1 were used as a starting point for this process. By identifying and exploiting the functional commonalties that exist among the preferred sensors, it was possible to develop a minimal set of EOA Level 1 hardware designs to accommodate the entire range of preferred sensors. Interface specifications were then developed for each of the candidate EOA designs in order to ensure compatibility with the preferred sensors technologies.

The optical sensor data base developed previously under Task 1 identified over 100 currently available optical sensors based on some 20 different technology implementations. Subsequent system evaluation efforts succeeded in identifying thirteen (13) "preferred" optical sensor technologies suitable for aircraft flight control and air data applications. These preferred sensor technologies (not in order of preference) are:

1) TDM Digital Code Plate
2) Analog Gradient Filter Plate/Wheel
3) Microbend Modulated
4) Reflective Diaphragm
5) Photo-Elastic
6) Absorption Edge Shift
7) Fabry-Perot Interferometer
8) WDM Digital Code Plate
9) Moving Diffraction Grating
10) Power-By-Light Remote Electric
11) Beam Interrupt/Pulse Count
12) Fluorescent TRD
13) Phosphorescent TRD

In order to reduce the number of unique EOA Level 1 designs required, these preferred sensors were grouped according to sensor technology class. This resulted in the identification of five (5) EOAs to accommodate these preferred sensor technologies. Selection of the candidate EOAs was based on availability of sensor technologies which are suitable for use in an aircraft multiplexed flight control system. As shown in Figure 3-28, the candidate EOAs (not in order of preference) are:

1) TDM Digital
2) TDM Analog
3) WDM Optical Spectrum Analyzer
4) PBL Remote Electrical
5) CW Intensity Modulated

The shaded portion of Figure 3-28 identifies those sensors which do not currently meet the operational or multiplexing requirements for aircraft flight control/air data sensors.

	Rotary Position	Linear Position	Angular Velocity	Tachometer/ Shaft Speed	Linear Acceleration	Temperature	Pressure	Sensor Classification	EOA Classification
TDM Digital Optical Code Plate	●	●					●	TDM Digital	TDM Digital
Beam Interrupt/Pulse Count	●	●		●					
Analog Gradient Filter Plate	●	●						TDM or WDM Analog Self-Referenced Intensity Modulated	TDM Analog / WDM Optical Spectrum Analyzer
Microbend Modulated					●		●		
Reflective Diaphragm						●	●		
Photo-Elastic							●		
Absorption Edge Shift						●			
Fabry-Perot Interferometer						●	●		
WDM Digital Optical Code Plate	●	●						WDM Optical Spectrum Analyzer	
Moving Diffraction Grating							●		
Phosphorescent						●		WDM Optical Spectrum TRD	WDM Optical Spectrum Analyzer
Fluorescent						●			
Power-By-Light (PBL)	●	●				●		Remote Electrical	Remote Electrical
Near Total Internal Reflection								CW Intensity Mod	CW Intensity Mod
Blackbody Radiation						●		Self Luminous	Self Luminous
Passive IR Analysis						●			
Raman/Raleigh Backscatter						●		Analog OTDR	Analog OTDR
Michelson Interferometer							●	Optical FMCW Interferometer	Optical FMCW Interferometer
Mach-Zehnder Interferometer					●				
Sagnac Interferometer			●			●			

= Sensors in the shaded regions are not suitable for use in an Aircraft Multiplexed Flight Control System

Figure 3-28 Flight Control Multiplexed EOA Development

Additional analysis concluded that it was possible to further reduce the number of candidate EOAs to four (4) by combining the CW Intensity Modulated with the TDM Digital EOA. The TDM Digital EOA used with optical code plate sensors is typically optimized for operation at a single frequency such as 100 MHz. The CW Intensity Modulated EOA is used exclusively for beam interrupt type rotary wheel speed sensors and will typically receive digital optical data anywhere in the range of DC to 100 KHz depending on wheel speed and size. By making only slight modifications to the receiver of the TDM Digital EOA it is possible to develop a common EOA capable of operating from DC to 100 MHz.

The optical spectrum TRD type sensors are generally not well suited for use in an aircraft multiplexed EOA due to the long sample time (10 - 100 ms) required to accurately measure sensor spectral decay. Nevertheless, they can readily be accommodated by a slight variation of the existing WDM Optical Spectrum Analyzer EOA design. The existing WDM EOA design is optimized for operation in the 750-950 nanometer range at both the transmitter and receiver. Spectral TRD sensors typically fluoresce (or phosphoresce) at a wavelength several hundred nanometers higher that the optical source excitation wavelength. Because of this fact, TRD sensors can only coexist with WDM based sensors if their returned spectrum is not in the 750-950 nanometer range, otherwise the relatively long optical decay time will interfere with the return signals from the other WDM sensors. In order to integrate a spectral decay sensor with conventional WDM based sensors in a single EOA, it is necessary to modify the WDM receiver to accommodate this spectral shift. For example, a spectral decay sensor with excitation centered at 850 nanometers and return spectrum centered at 1000 nanometers could easily be accommodated in the existing WDM EOA by merely adding another diode optimized for this wavelength onto the photodiode array. In this instance, the relatively long decay times associated with spectral decay sensors would not affect operation of the other WDM sensors.

Detailed Level 1 designs for each of the four EOAs are presented in Appendix D. Each of the EOA designs are based upon a Multiple Source/Single Detector (MSSD) multiplexing approach which was the optimal approach identified earlier. To minimize system optical interconnect losses, the EOA receiver designs incorporate a non-reciprocal power combiner constructed by combining all of the sensor receive fibers into a single fiber bundle. This approach eliminates the physical splitting losses (10 log N) and excess losses associated with a fused biconical type reciprocal power combiner. Anticipated losses for this type of multiplexing will depend on the number of receive fibers and the surface area of the receiver photodetector, but can generally be assumed to be less than 3 dB. Although this power combiner can be considered to be a somewhat "specialized" component, it is fairly easily constructed. This approach is acceptable from a maintainability and integrated logistics support viewpoint since the combiner is confined to the EOA module itself.

Additional specialized components which may be required to implement the candidate EOAs include: 1) TDM high power optical source capable of coupling +4 dBm optical power into 100/140 micron step-index optical fiber, 2) WDM broadband integrated light source capable of providing 200 nanometers broadband light with channel density approaching 10 microwatts per nanometer into 100/140 micron step-index optical fiber. 3) WDM integrated optical spectrum analyzer for demultiplexing 10 to 12 bit WDM signals, and 4) planar waveguide couplers for use in WDM broadband optical sources and self-referencing sensors.

The EOA interface covering a general class of sensors can be specified at this time. Detailed interface control documents for each sensor type can be developed later as part of a cooperative agreement between the individual sensor and EOA manufacturers. Interface specifications for EOAs are included in Appendix D.

3.2.5 Task 2.5 - Layout of Sensor/Actuator to Controller Interface

This task addressed the interconnection between flight control and air data sensors, actuators, EOAs, and flight controllers. The manner in which the flight and propulsion control systems are integrated into the VMS bus and avionics multiplex bus was also addressed. Physical layout criteria was based on the F-15/SMTD aircraft.

Before beginning the task of EOA airframe integration, the airframe sensors were arranged into logical groups according to sensor function. As shown in Figure 3-29, this resulted in the identification of 9 EOA functional groupings for a single channel (non-redundant) flight control system. Each functional grouping was then assigned a range of EOA technologies with which it is compatible. Most of the EOA functional groups are compatible with a wide range of technologies and the lack of a strong discriminator makes it impossible to identify a singular optimized technology at this time. Exceptions to this are the interferometric inertial reference sensors which will not be remotely multiplexed, and the rotary wheel speed sensor which is currently only compatible with TDM Digital EOA.

SENSOR				EOA		
TYPE	NAME	SYMBOL	REDUN	GROUP	REDUN	CLASS
Linear Accelerometer	Lateral Acceleration	NY	2 x 2	Integrated Inertial Reference Assembly	x 2	Non Multiplexed Optical Interferometer
	Normal Acceleration	NZ	2 x 2			
Rate Gyroscope	Aircraft Pitch Rate	PITCH	2 x 2			
	Aircraft Roll Rate	ROLL	2 x 2			
	Aircraft Yaw Rate	YAW	2 x 2			
Linear Position	Roll Stick Position	RSP	1 x 4	Pilot Control	x 4	TDM Digital
	Pitch Stick Position	PSP	1 x 4			
	Yaw Pedal Position	YPP	1 x 4			
	Throttle Lever Angle	TLA	2 x 4			
	Canard	CNRD	2 x 4	Pitch Control	x 4	TDM Analog
	Stabilator	STAB	2 x 4			
	Nose Wheel Steering	NWS	1 x 2	Air Inlet Control	x 2	
	Air Inlet Controller	AIC	2 x 2			WDM Optical Spectrum Analyzer
	Nozzle Controller	NC	4 x 4	Nozzle Control	x 4	
	Thrust Reverser Vane	TRV	2 x 4			
	Aileron	AIL	2 x 2	Yaw Control	x 2	
	Flaperon	FLAP	2 x 2			
Rotary Position	Rotary Rudder	RUD	2 x 2			PBL Remote Electrical
	Angle Of Attack	AOA	2 x 4	Alpha Control	x 4	
	Power Lever Angle	PLA	2 x 4			
Pressure	Pitot Pressure	PT	2 x 2	Air Data	x 2	
	Static Pressure	PS	2 x 2			
Temperature	Air Data Temperature	ADT	2 x 1			
Speed	Main Landing Gear	MLG	2 x 1	Skid Control	x 1	TDM Digital

SENSOR TOTAL = 126 EOA TOTAL = 25

= Sensors in the shaded regions are not suitable for use in remote multiplexed aircraft EOA systems.

Figure 3-29 Aircraft EOA Functional Groupings

Next, a conceptual design for integrating the EOA functional groups into an airframe was developed using F-15/SMTD physical layout criteria as shown in Figure 3-30. It is recommended that the EOA to flight controller interface be MIL-STD-1773 compatible in order to maintain compatibility with existing 1553 based data acquisition hardware and test equipment.

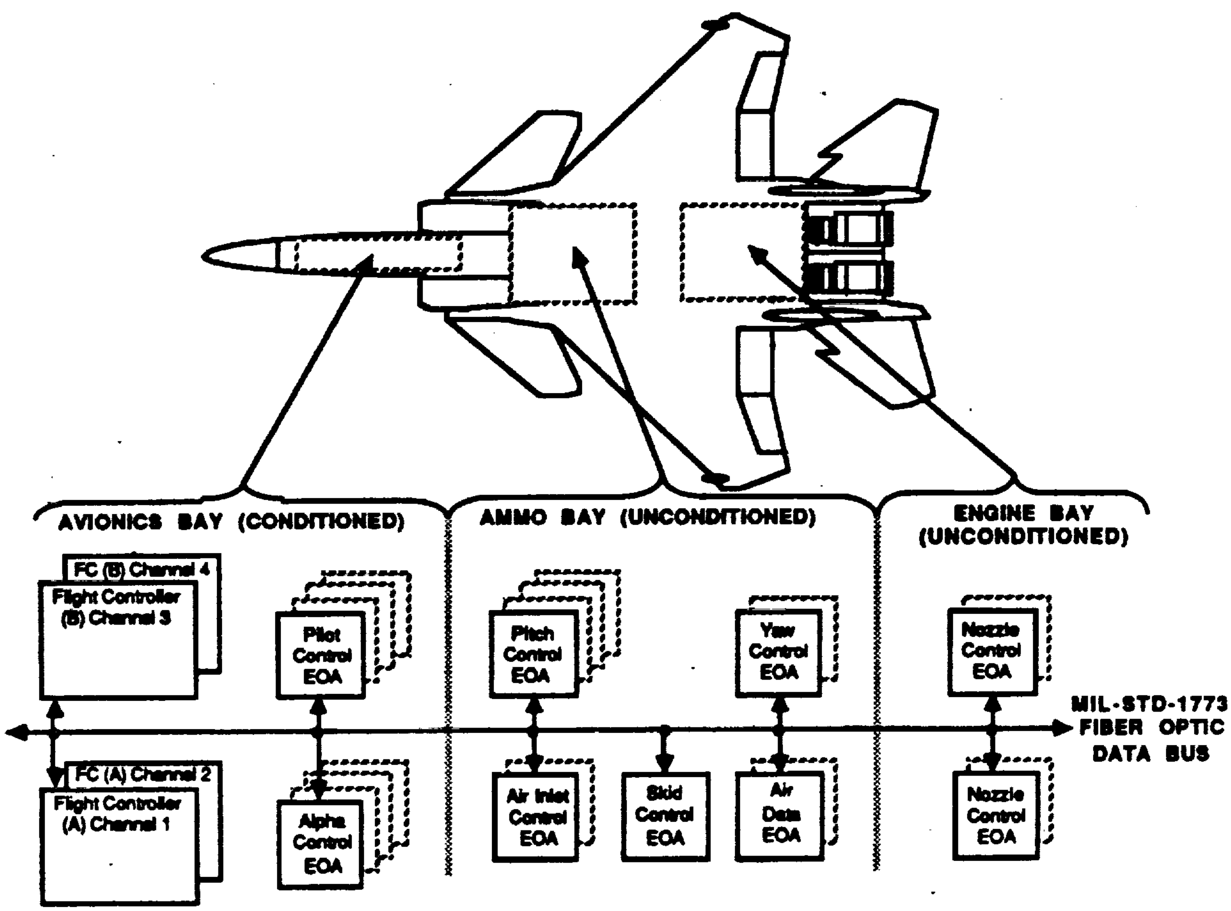


Figure 3-30 F-15/SMTD Aircraft EOA Physical Layout

The manner in which an EOA based flight and propulsion control systems might be integrated into an advanced aircraft VMS was also addressed. The Air Force PAVE PILLAR advanced architecture concept served as the starting point for this effort. Current VMS design concepts employ remote multiplexing of electrical sensors via remote terminal units connected to a VMS computer (flight controller) by a high speed fiber optic data bus. EOA technology can easily be incorporated into advanced VMS architecture as a pre-planned product improvement. Upgrading a PAVE PILLAR architecture to incorporate EOA technology is accomplished by removing the existing electrical sensor interface modules and replacing them with EOA modules. The sensor and interconnect cable would correspondingly be changed to fiber optic.

3.2.6 Task 2.6 - Components Redundancy Design

This task addressed EOA redundancy and fault tolerance as a means of satisfying system integrity requirements. A prerequisite to the development of a totally integrated fiber optic control system is an understanding of the present day electrical implementation. Electronic flight control system architectures have evolved to economically and reliably meet aircraft requirements for flight safety and can therefore serve to illustrate several key aspects of the problem. F-15/SMTD flight control system architecture used in this study serves as a case in point. The F-15/SMTD employs a quad redundant digital flight controller configured as two dual redundant controllers which are separated in the aircraft to enhance survivability. Each of the four processing channels in the flight controller have access to all available electronic sensor information and can therefore function as an autonomous processing unit. This arrangement provides a high degree of system integrity which allows the flight control system to continue operating even after two successive failures of a sensing or processing resource. To reduce the amount of wiring required between the sensors and flight controllers, electronic sensor information is multiplexed within the individual flight controllers and shared between processor channels over a dedicated cross channel data link. The ability to "cross wire" sensors to individual flight controllers becomes increasingly difficult with optical sensors due to power budget restrictions. As indicated in Figure 3-31, this problem must be overcome through the use of extensive cross channel data monitoring.

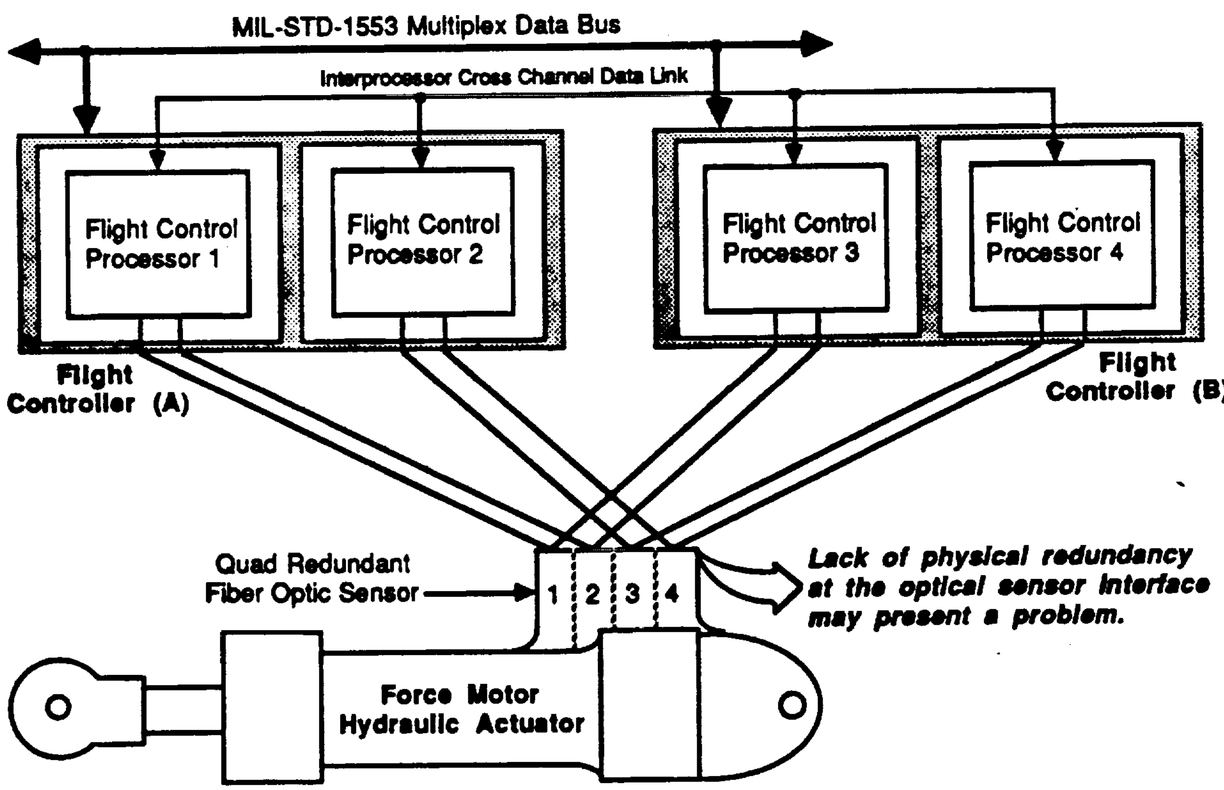


Figure 3-31 F-15/SMTD Sensor Redundancy Implementation

4.0 DISCUSSION OF RESULTS

The objective of this contract was to evaluate various optical sensor modulation technologies and to design an optimal Electro-Optic Architecture (EOA) for servicing remote clusters of sensors and actuators in advanced aircraft flight control systems. This study was part of a multi-year initiative under the Fiber Optic Control System Integration (FOCSI) program to design, develop, and test a totally integrated fiber optic flight/propulsion control system for application to advanced aircraft. This program signalled the start of FOCSI Phase II and will provide the foundation for future activities in the areas of of advanced component development and test.

The results of **Task 1** system evaluation efforts indicate two points: (1) no singular optical sensor technology can be optimized for all aircraft sensor applications, and (2) due to the relatively immature state of optical sensor technology, no strong discriminator currently exists upon which to base the selection of an "optimal" EOA technology for any given sensor application. However, the results of Task 1 can be used to identify several "preferred" optical sensor technologies suitable for aircraft flight control and air data sensing applications. These preferred technologies are:

- **TDM Digital Optical Code Plate**
- **Beam Interrupt/Pulse Count**
- **Analog Gradient Filter Plate**
- **Microbend Modulated**
- **Reflective Diaphragm**
- **Photo-Elastic**
- **Absorption Edge Shift**
- **Fabry-Perot Interferometer**
- **WDM Digital Optical Code Plate**
- **Moving Diffraction Grating**
- **Phosphorescent TRD**
- **Fluorescent TRD**
- **Power-By-Light Remote Electric**

By identifying and exploiting the functional commonalties that existed among these sensors , it was possible to identify four "preferred" EOA configurations the entire range of preferred optical sensor technologies. The preferred EOA configurations are:

- **Time Division Multiplexed Digital**
- **Time Division Multiplexed Analog**
- **Wave Division Multiplexed Optical Spectrum Analyzer**
- **Power-By-Light (PBL) Remote Electrical.**

The results of **Task 2** design efforts indicate that it is possible to develop a set of four common EOA modules that are compatible with a wide range of promising optical sensor technologies. Interface specifications were then developed for each of the candidate EOA designs in order to ensure compatibility with the preferred sensors technologies. Specialized components requiring further development prior to construction of an integrated EOA system were identified and include:

1) TDM High Power Optical Source
2) WDM Broadband Integrated Source
3) WDM Integrated Optical Spectrum Analyzer
4) Planar Waveguide Passive Coupler

Conceptual designs were developed for each of these components. Anticipated FOCSI follow on activities will be directed towards the construction and evaluation of these components, the preferred optical sensors, and associated EOAs ultimately leading to a flight test program to evaluate the suitability of optical sensor technology for advanced aircraft applications

This page intentionally left blank.

APPENDIX A

COOPERATIVE FIBER OPTIC SENSOR MANUFACTURERS

McDonnell Aircraft Company would like to express its appreciation to the following manufacturers who supplied valuable technical information for the optical sensor data base.

- **Accufiber, Incorporated**
  Vancouver, WA
- **Allied Precision Electronics**
  College Station, TX
- **Aster Corporation**
  Milford, MA
- **AT&T Corporation**
  Los Angeles, CA
- **Aurora Optics**
  Blue Bell, PA
- **Babcock & Wilcox**
  Alliance, OH
- **BEI Motion Systems**
  Little Rock, AR
- **Conax Buffalo Corporation**
  Buffalo, NY
- **Eaton/Cuttler Hammer Corp.**
  Shawnee Mission, KS
- **EG&G Fiber Optics**
  Burlington, MA
- **ELDEC Corporation**
  Lynwood, WA
- **EOTec Corporation**
  West Haven, CT
- **Fiber Optic Sensor Tech.**
  Ann Arbor, MI
- **FSI/Fork Standards, Inc.**
  Lombard, IL
- **General Electric Company**
  Cincinnati, OH
- **Hewlett-Packard**
  Rolling Meadows, IL
- **Honeywell, Incorporated**
  Minneapolis, MN
- **Hughes Research Labs**
  Goleta, CA
- **Inland Motor Corporation**
  Radford, VA
- **Litton Poly-Scientific**
  Blacksburg, VA

- Luxtron Corporation
  Mountain View, CA
- McDonnell Douglas Astronautics
  Huntington Beach, CA
- Mechanical Technology, Inc.
  Latham, NY
- Metricor
  Woodinville, WA
- Optelecom, Incorporated
  Gaithersburg, MD
- Optic Measurement Controls, Inc
  The Woodlands, TX
- Optical Technologies, Inc.
  Herndon, VA
- OPW/Dover Corporation
  Cincinnati, OH
- Parker Bertea Aerospace
  Irvine, CA
- Rosemount, Incorporated
  Bridgeton, MO
- Simmonds Precision Products
  Vergennes, VT
- Singer Kearfott
  Black Mountain, NC
- Statham Transducer
  Oxnard, CA
- TACAN Aerospace Corporation
  Carlsbad, CA
- Tedeco/Aeroquip Corporation
  Glenolden, PA
- Teledyne Ryan Electronics
  San Diego, CA
- Untied Technologies Research
  East Hartford, CT
- Vanzetti Systems, Inc.
  Stoughton, MA
- Williamson Corporation
  Concord, MA
- York Technology
  Princeton, NJ

This page intentionally left blank.

APPENDIX B

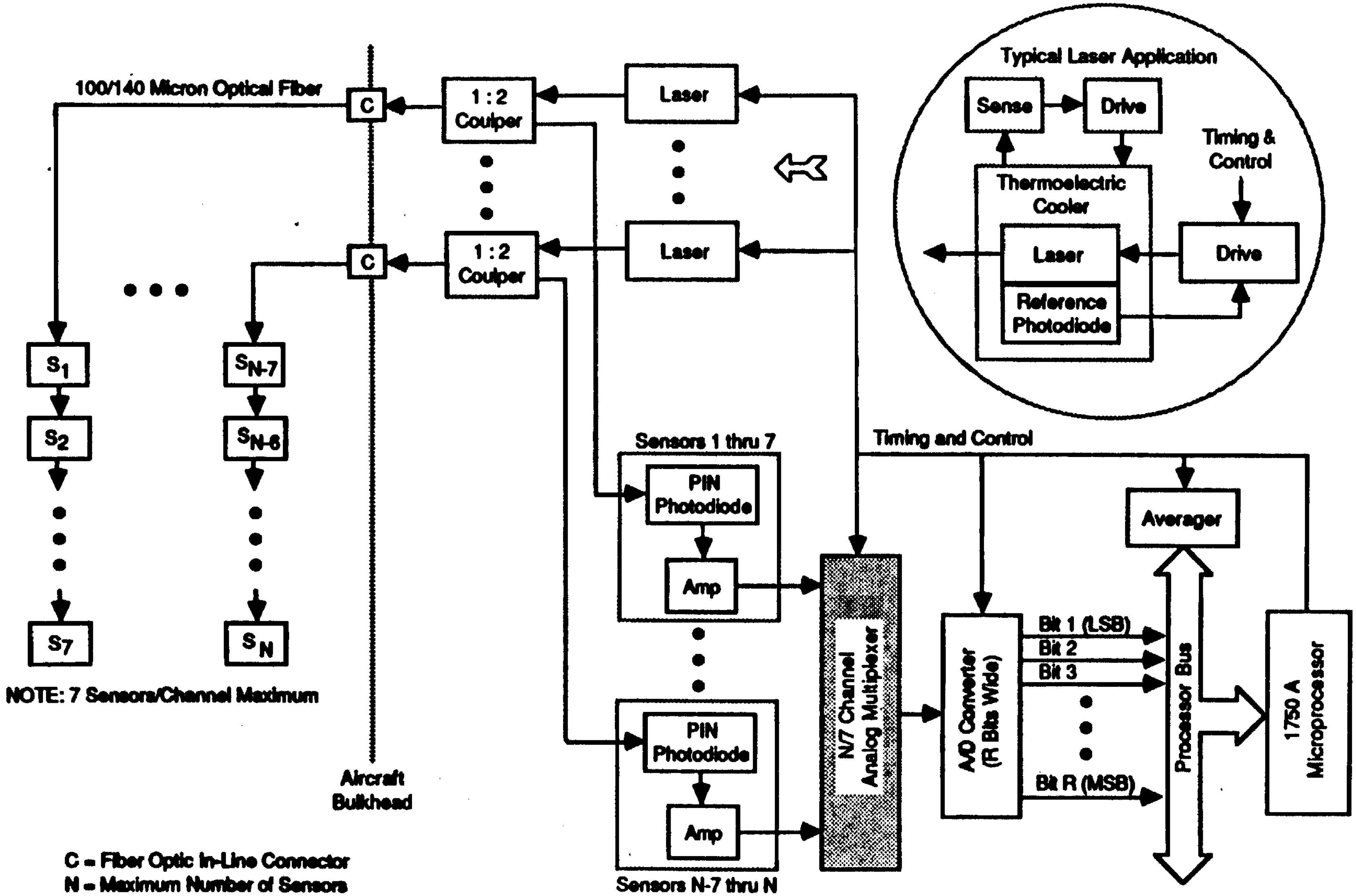
CANDIDATE MULTIPLEXED ELECTRO-OPTIC ARCHITECTURE DESIGNS

PAGE A-4 INTENTIONALLY BLANK

PRECEDING PAGE BLANK NOT FILMED

OTDR RALEIGH BACKSCATTER SENSOR INTERFACE

MULTIPLE SOURCE/MULTIPLE DETECTOR APPROACH

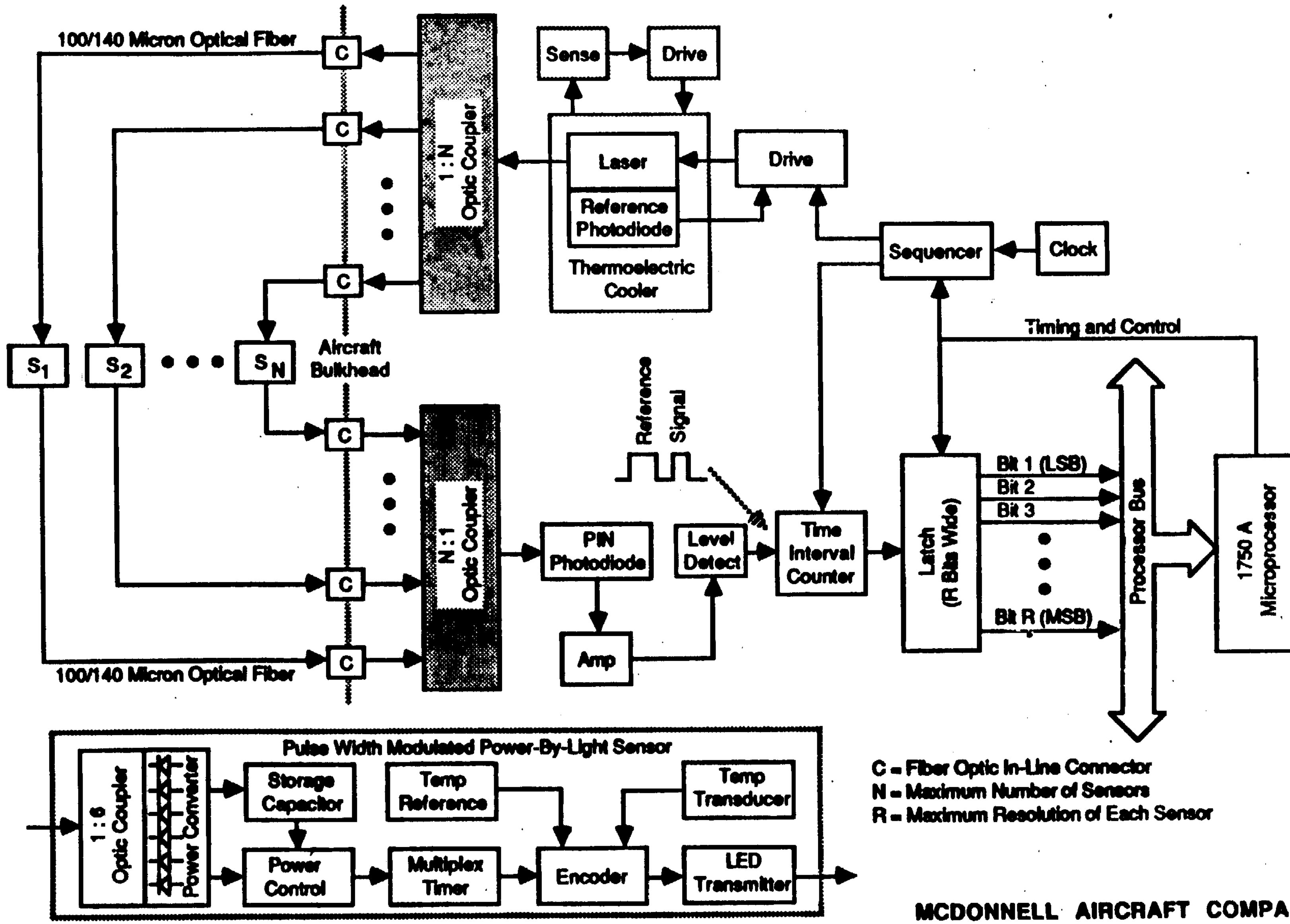


C = Fiber Optic In-Line Connector
N = Maximum Number of Sensors
R = Maximum Resolution of Each Sensor

MCDONNELL AIRCRAFT COMPANY

LASER POWER-BY-LIGHT SENSOR INTERFACE

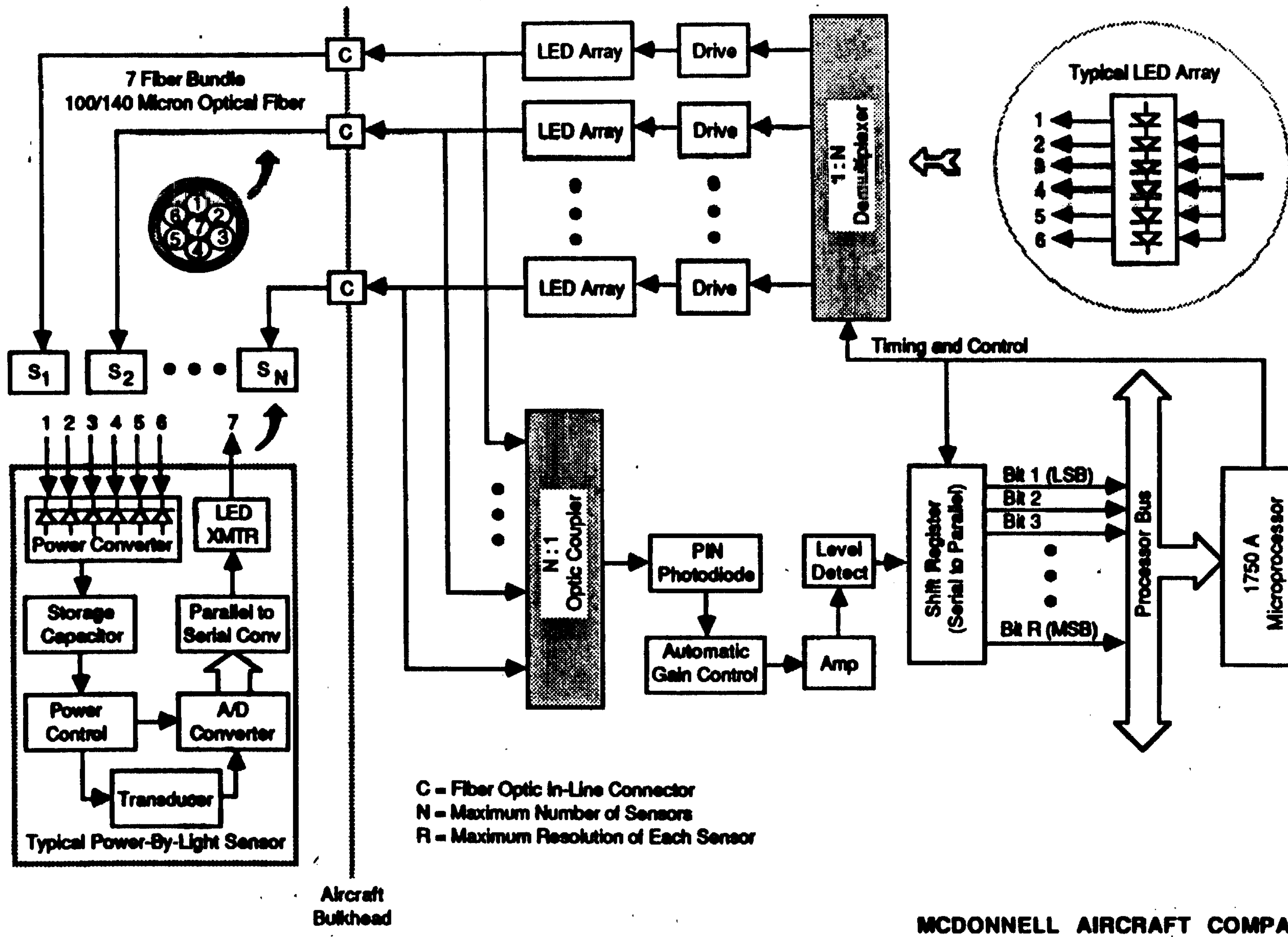
SINGLE SOURCE/SINGLE DETECTOR APPROACH



C = Fiber Optic In-Line Connector
N = Maximum Number of Sensors
R = Maximum Resolution of Each Sensor

MCDONNELL AIRCRAFT COMPANY

LED POWER-BY-LIGHT SENSOR INTERFACE
MULTIPLE SOURCE/SINGLE DETECTOR APPROACH

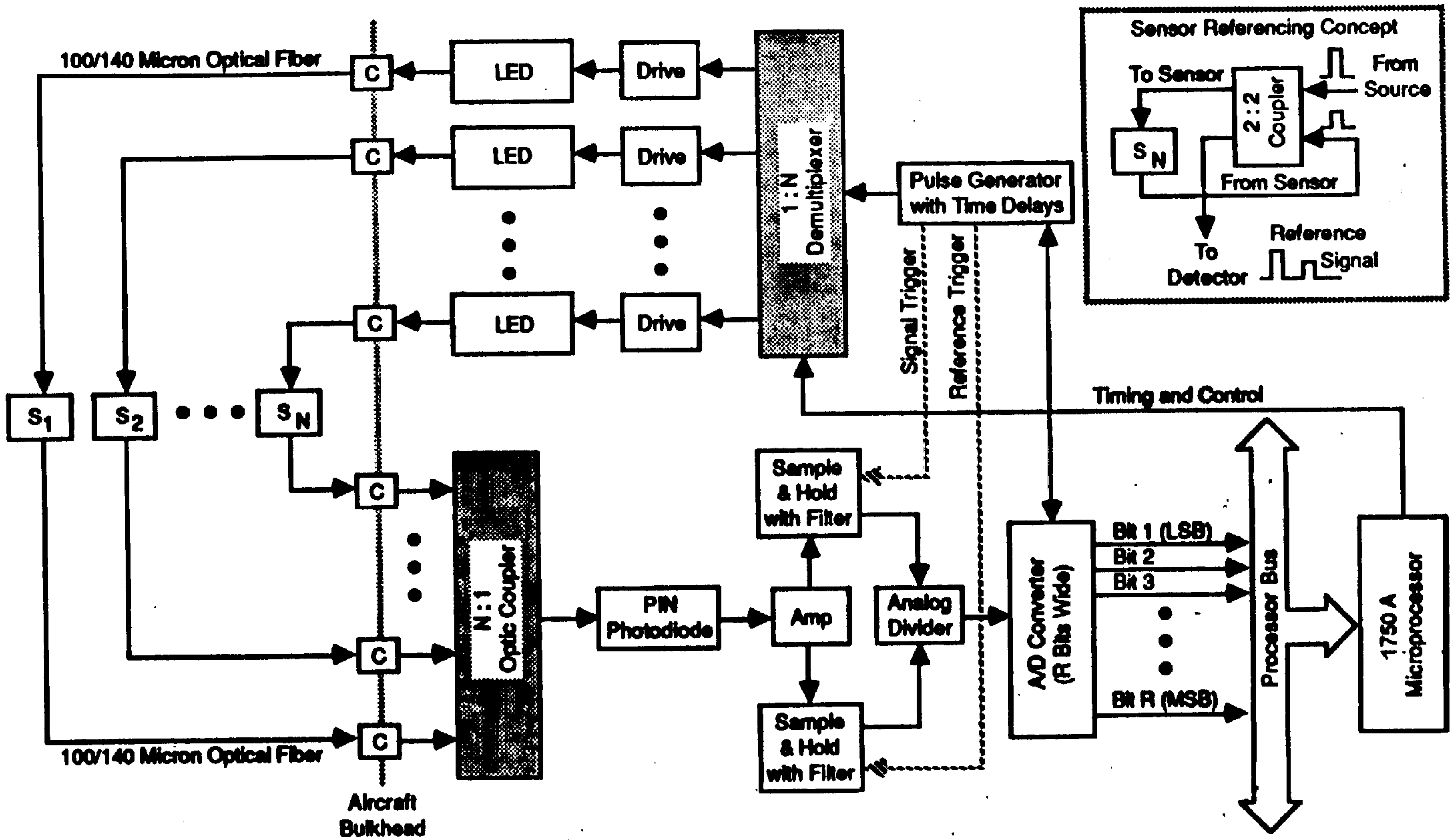


C = Fiber Optic In-Line Connector
N = Maximum Number of Sensors
R = Maximum Resolution of Each Sensor

MCDONNELL AIRCRAFT COMPANY

TDIN ANALOG GRADIENT FILTER PLATE INTERFACE

MULTIPLE SOURCE/SINGLE DETECTOR APPROACH

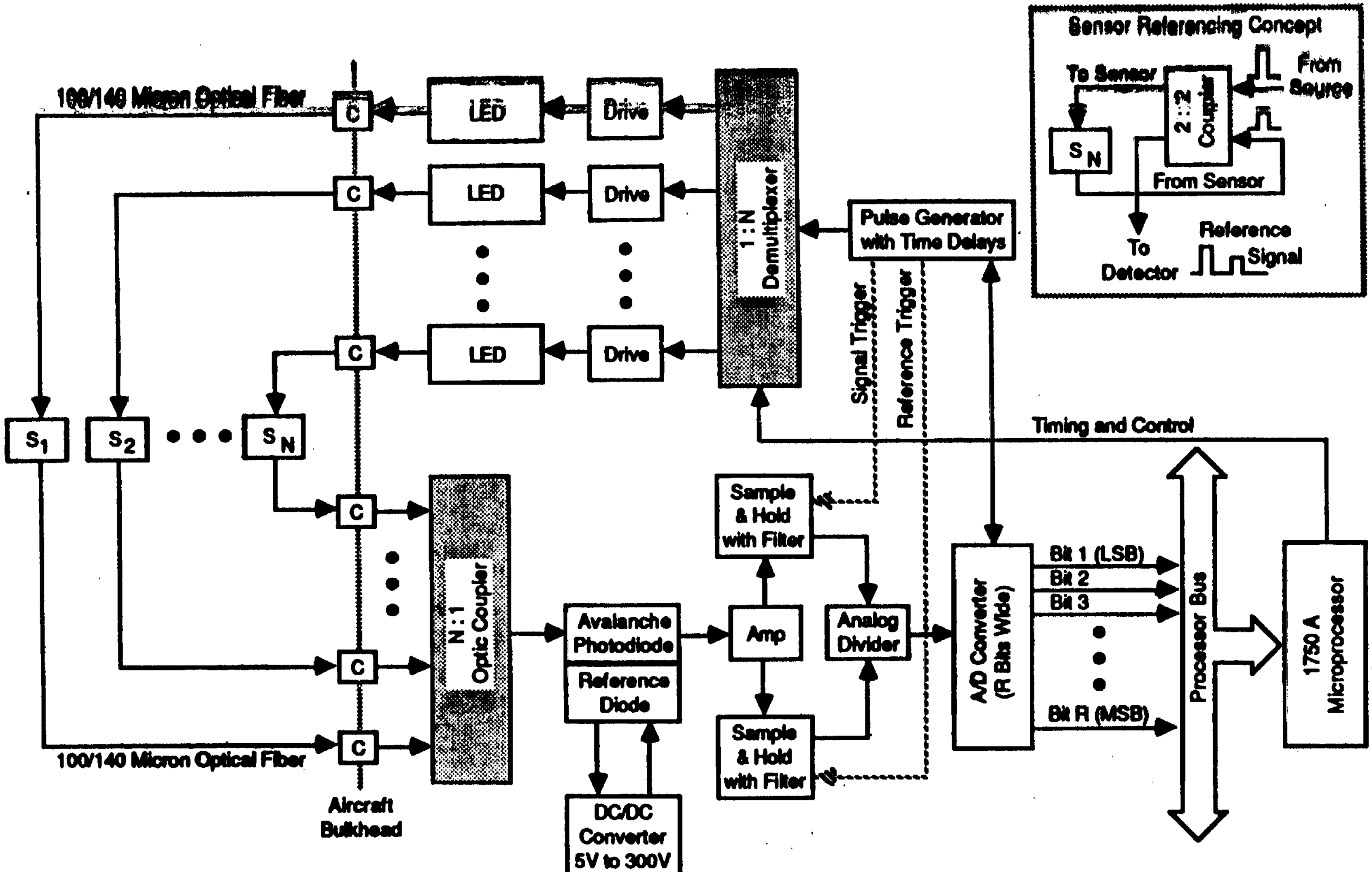


C = Fiber Optic In-Line Connector
N = Maximum Number of Sensors
R = Maximum Resolution of Each Sensor

MCDONNELL AIRCRAFT COMPANY

TDIN ABSORBTION EDGE SHIFT SENSOR INTERFACE

MULTIPLE SOURCE/SINGLE DETECTOR APPROACH

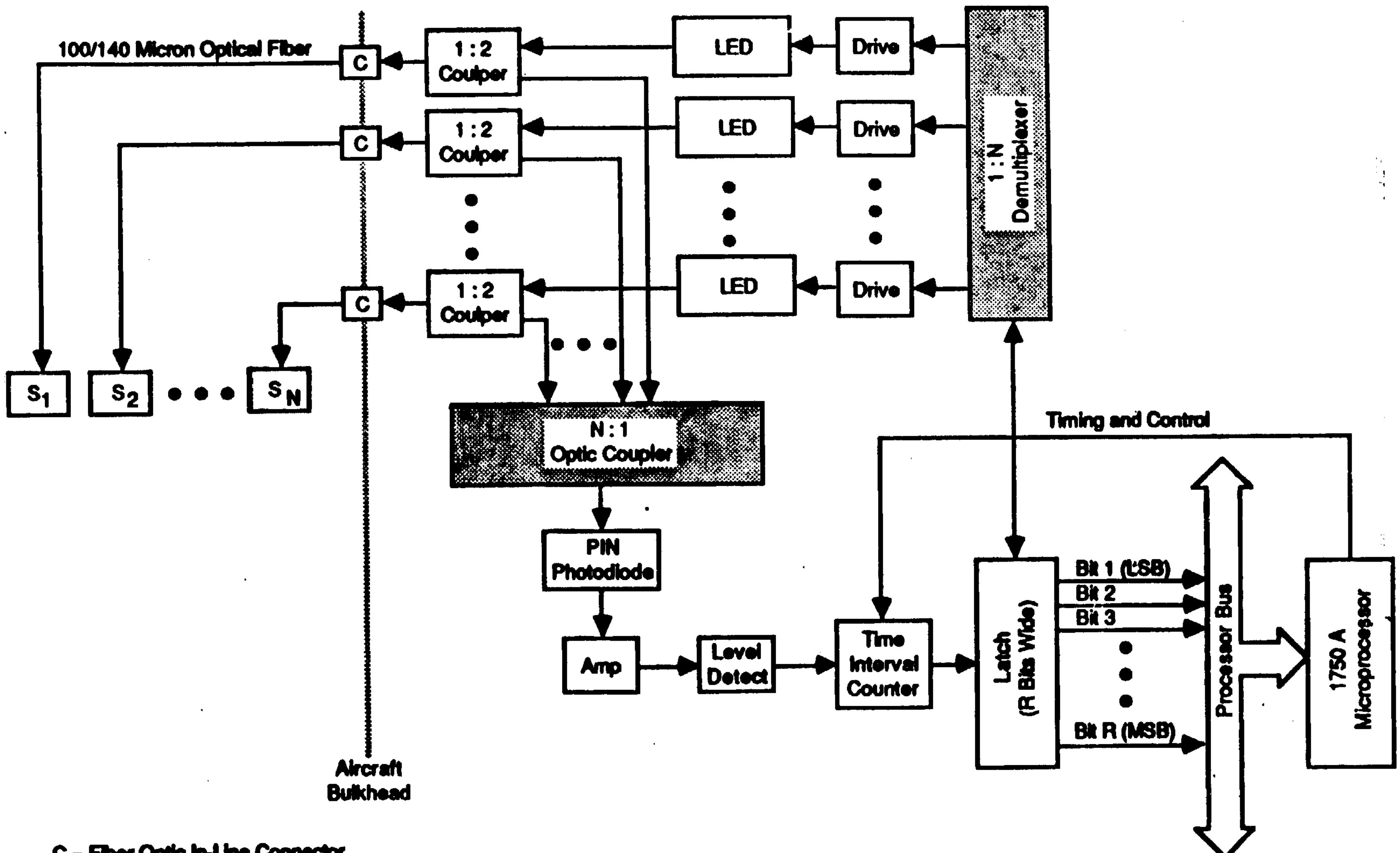


C = Fiber Optic In-Line Connector
N = Maximum Number of Sensors
R = Maximum Resolution of Each Sensor

MCDONNELL AIRCRAFT COMPANY

TDM BEAM INTERRUPT SENSOR INTERFACE

MULTIPLE SOURCE/SINGLE DETECTOR APPROACH

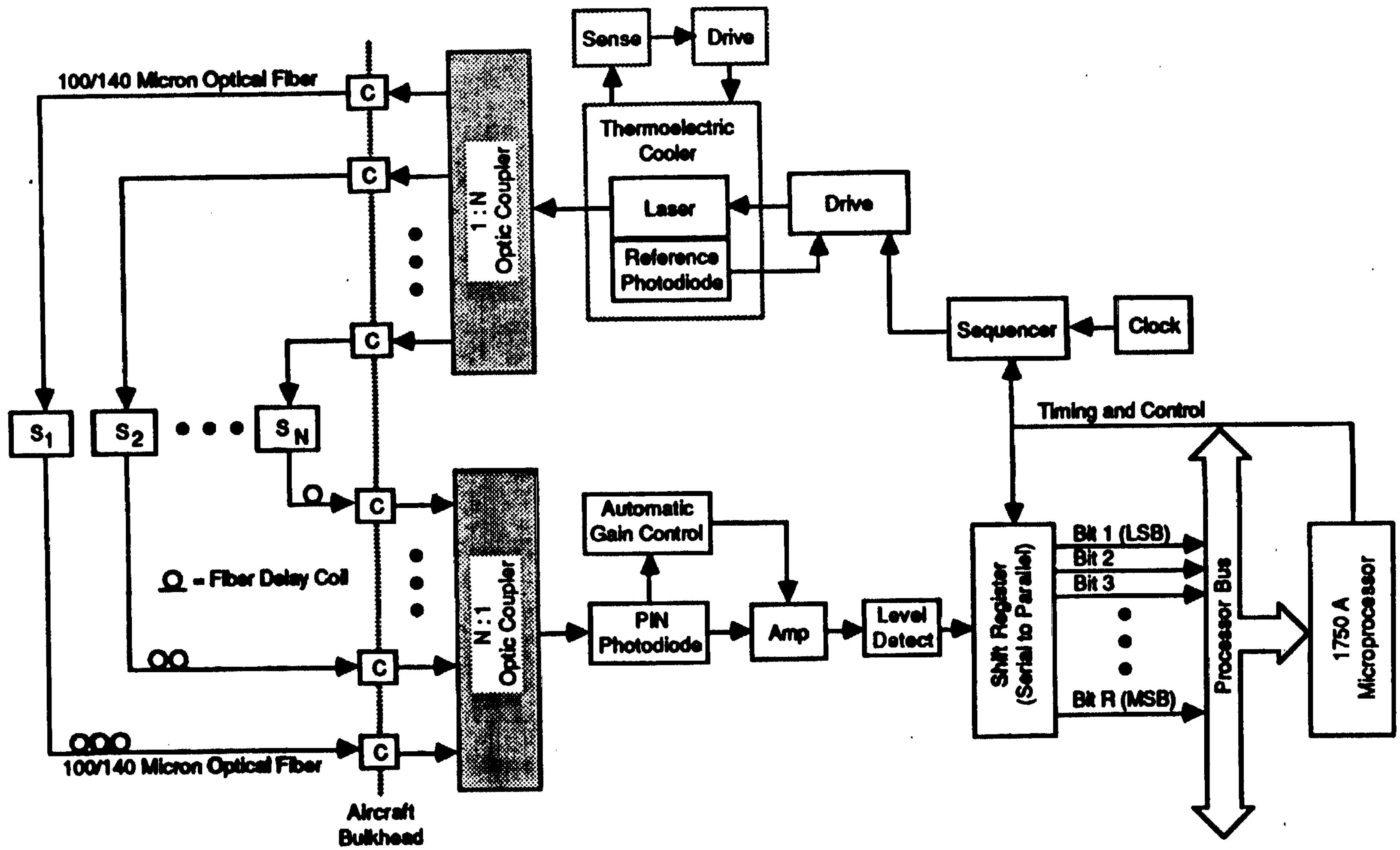


C = Fiber Optic In-Line Connector
N = Maximum Number of Sensors
R = Maximum Resolution of Each Sensor

MCDONNELL AIRCRAFT COMPANY

TDM DIGITAL OPTICAL CODE PLATE INTERFACE

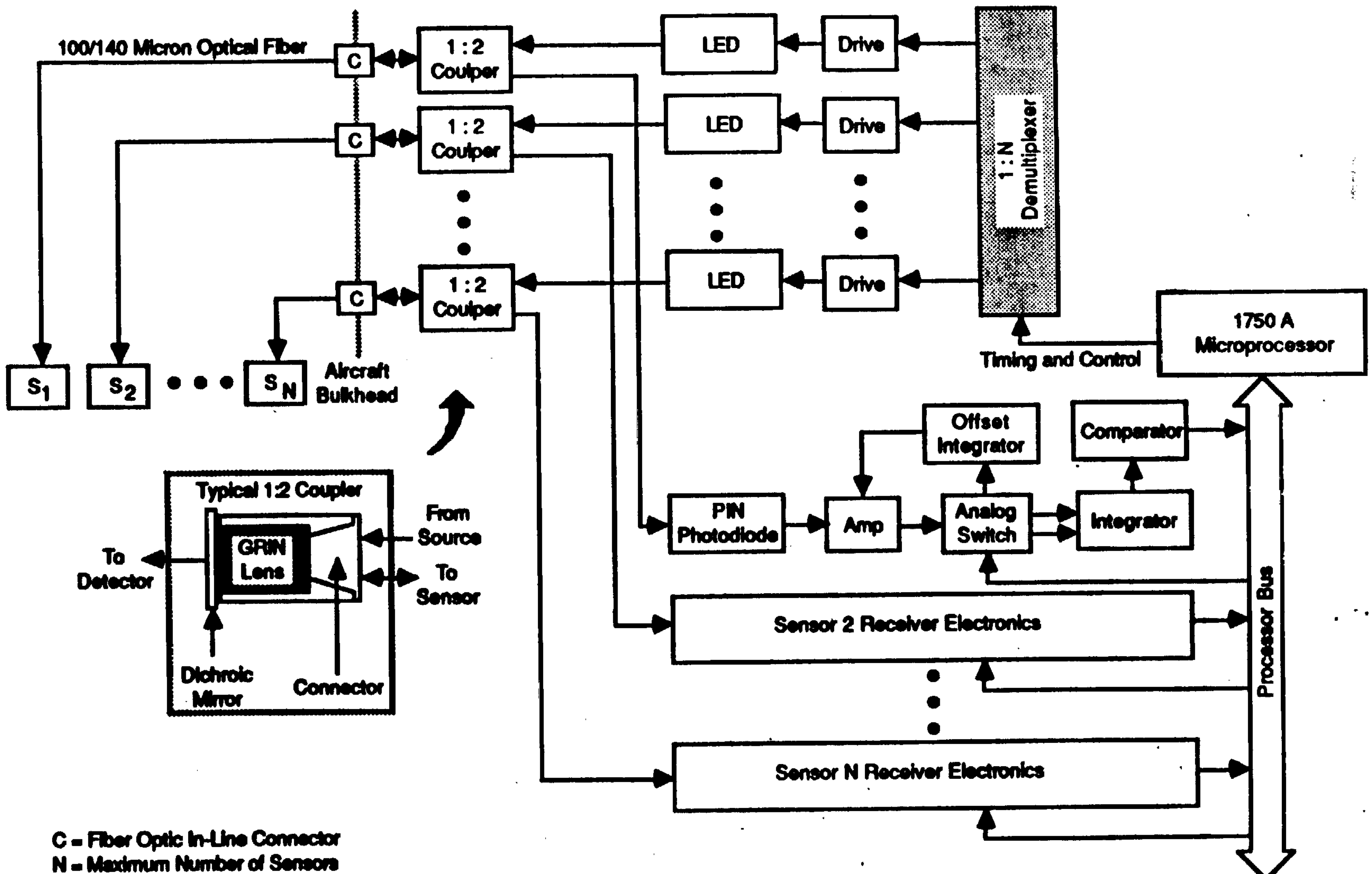
SINGLE SOURCE/SINGLE DETECTOR APPROACH



C = Fiber Optic In-Line Connector
N = Maximum Number of Sensors
R = Maximum Resolution of Each Sensor

MCDONNELL AIRCRAFT COMPANY

FLUORESCENT TRD SENSOR INTERFACE
MULTIPLE SOURCE/MULTIPLE DETECTOR APPROACH

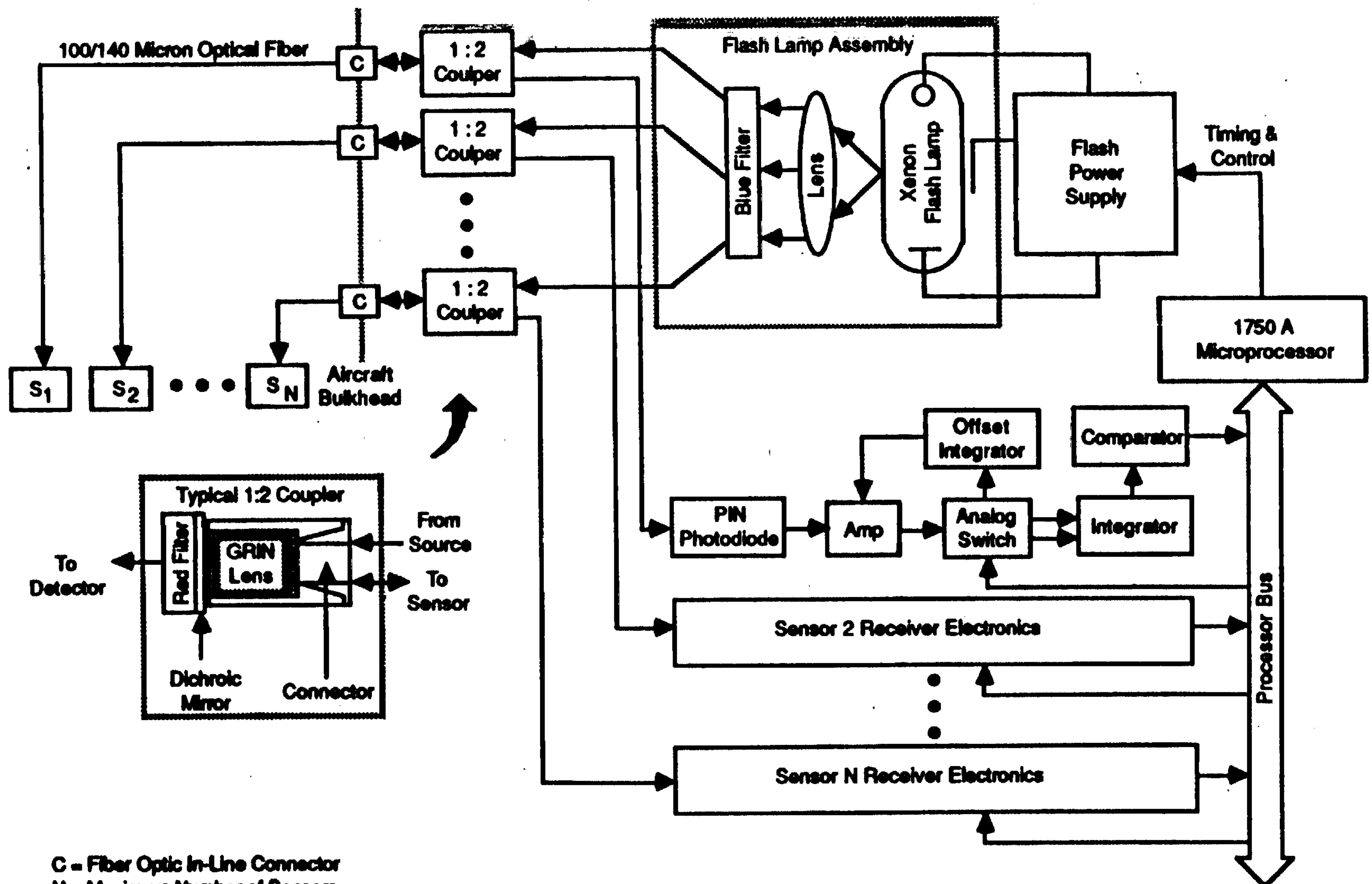


C = Fiber Optic In-Line Connector
N = Maximum Number of Sensors
R = Maximum Resolution of Each Sensor

MCDONNELL AIRCRAFT COMPANY

PHOSPHORESCENT TRD SENSOR INTERFACE

SINGLE SOURCE/MULTIPLE DETECTOR APPROACH

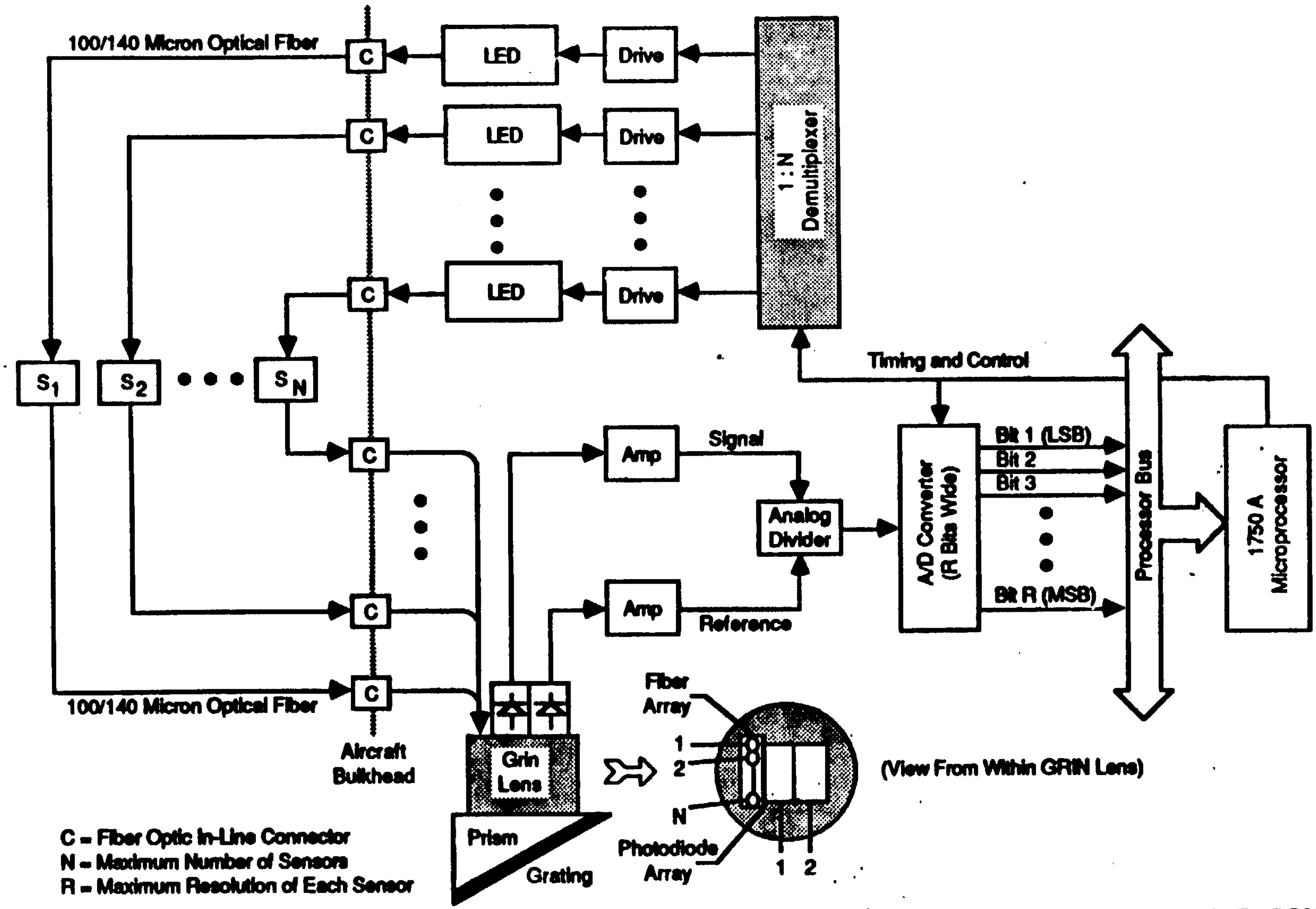


C = Fiber Optic In-Line Connector
N = Maximum Number of Sensors
R = Maximum Resolution of Each Sensor

MCDONNELL AIRCRAFT COMPANY

WDIN ABSORPTION EDGE SHIFT SENSOR INTERFACE

MULTIPLE SOURCE/SINGLE DETECTOR APPROACH

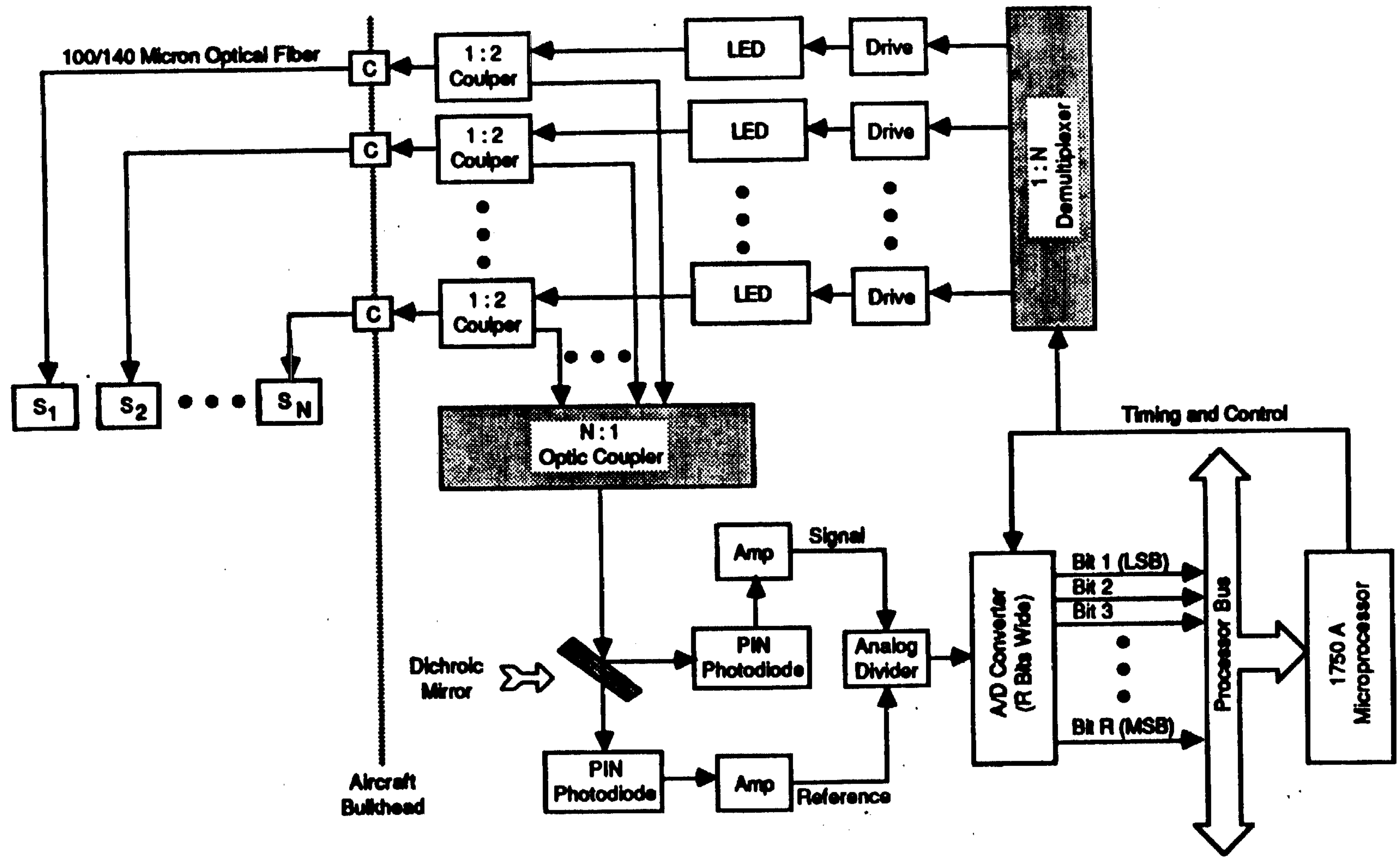


C = Fiber Optic In-Line Connector
N = Maximum Number of Sensors
R = Maximum Resolution of Each Sensor

MCDONNELL AIRCRAFT COMPANY

WDIN FABRY-PEROT INTERFEROMETER INTERFACE

MULTIPLE SOURCE/SINGLE DETECTOR APPROACH

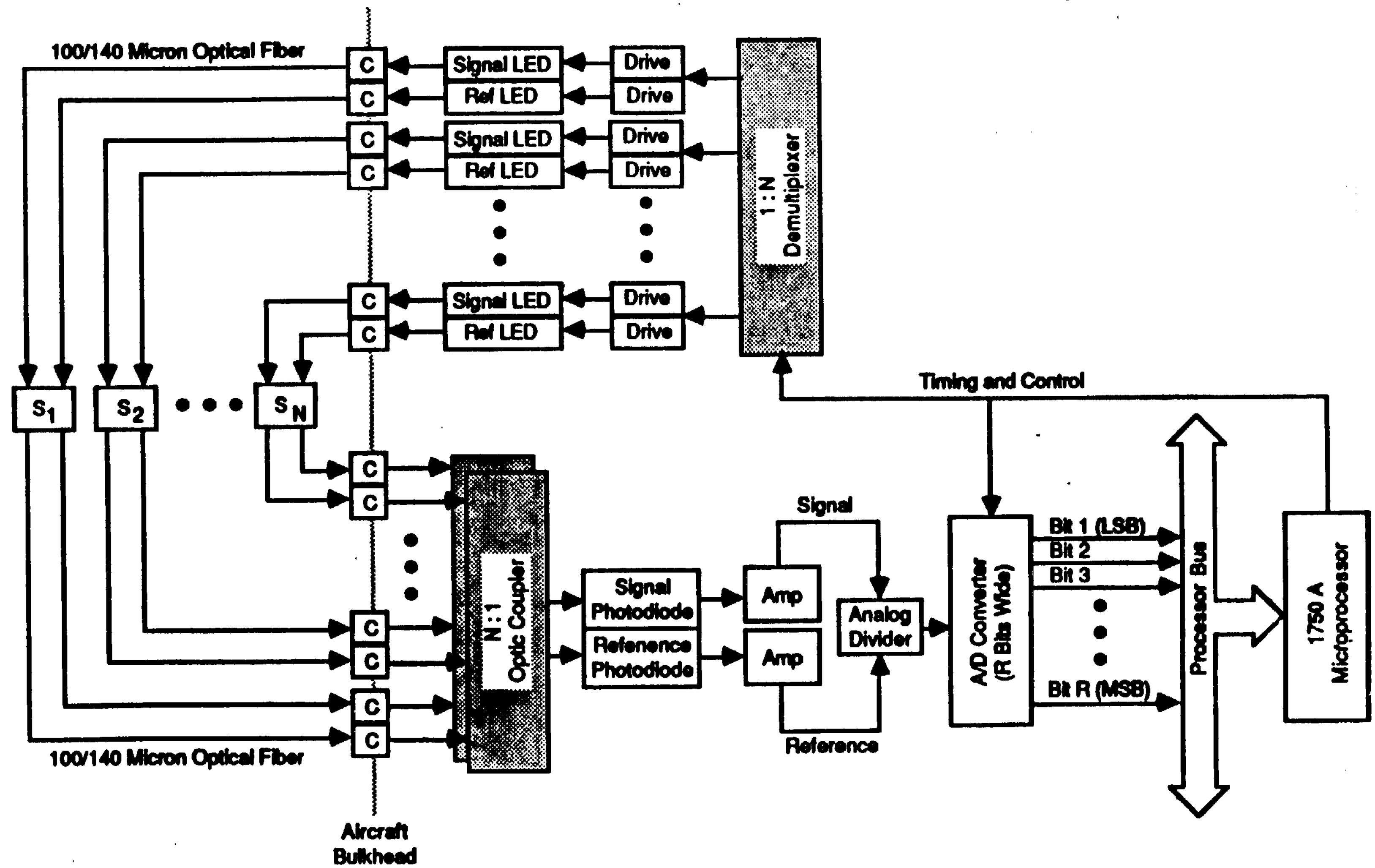


C = Fiber Optic In-Line Connector
N = Maximum Number of Sensors
R = Maximum Resolution of Each Sensor

MCDONNELL AIRCRAFT COMPANY

WDIN ANALOG GRADIENT FILTER PLATE INTERFACE

MULTIPLE SOURCE/SINGLE DETECTOR APPROACH

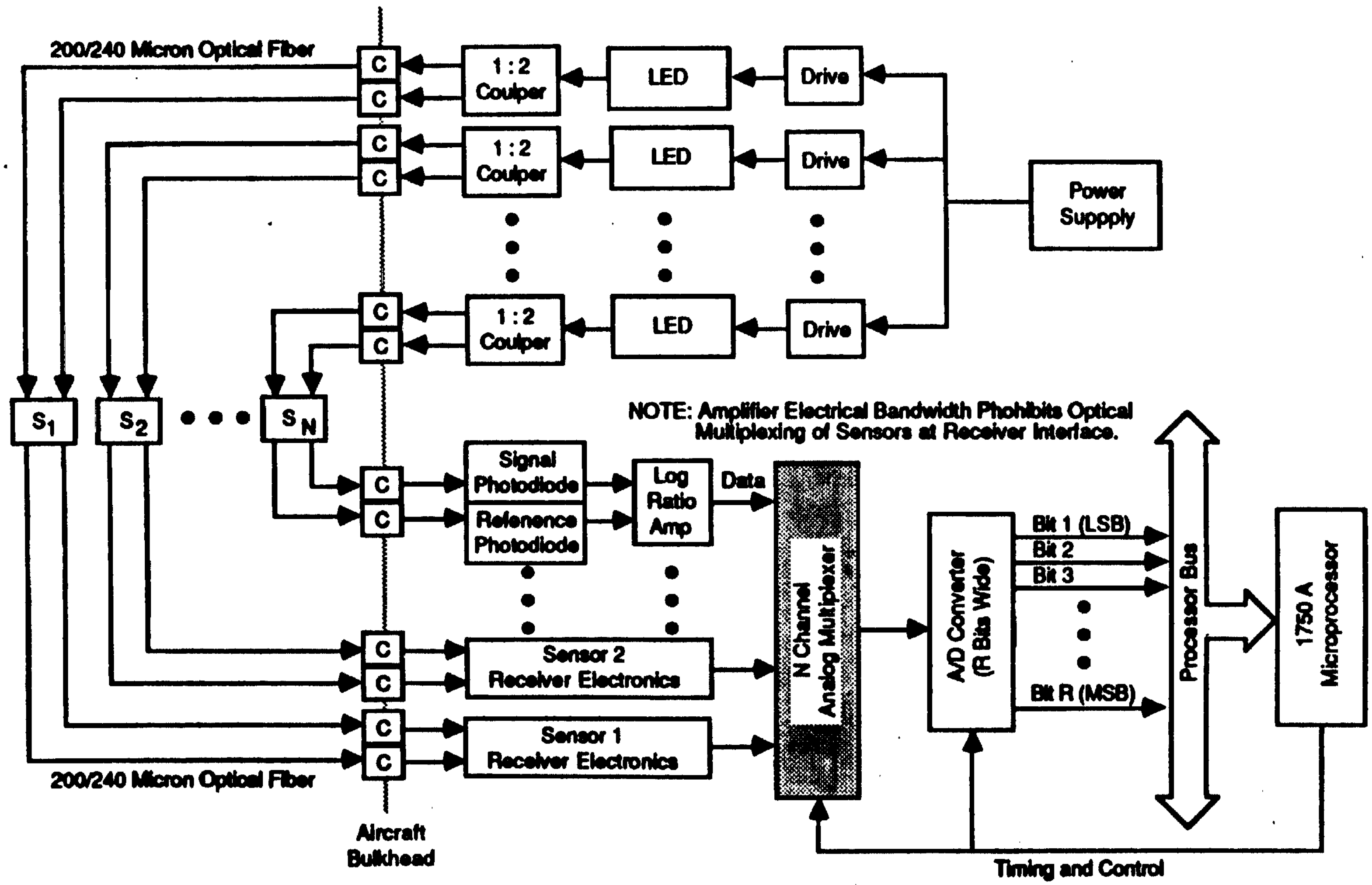


C = Fiber Optic In-Line Connector
N = Maximum Number of Sensors
R = Maximum Resolution of Each Sensor

MCDONNELL AIRCRAFT COMPANY

WDIN MICROBEND MODULATED SENSOR INTERFACE

MULTIPLE SOURCE/MULTIPLE DETECTOR APPROACH



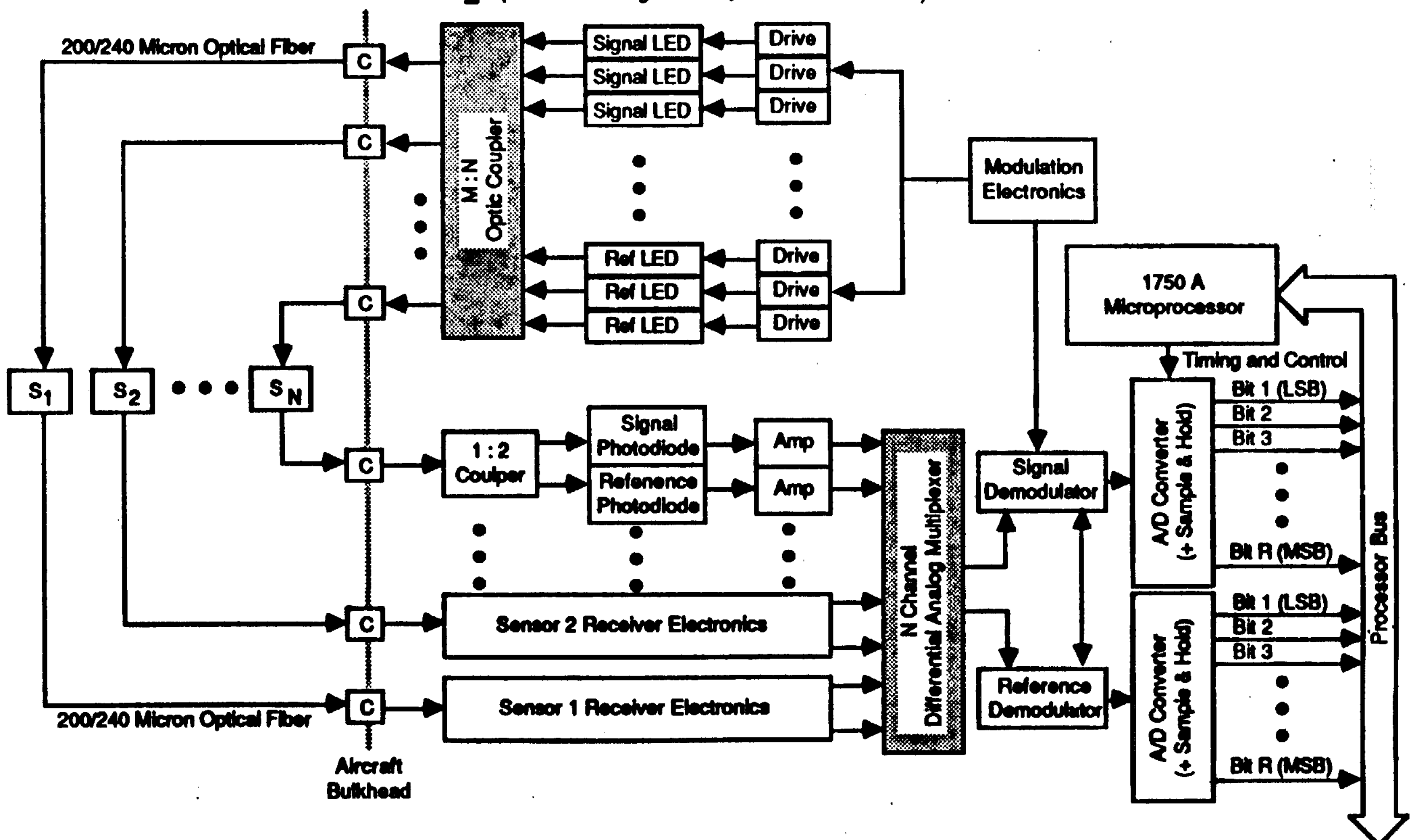
C = Fiber Optic In-Line Connector
N = Maximum Number of Sensors
R = Maximum Resolution of Each Sensor

MCDONNELL AIRCRAFT COMPANY

WDIN PHOTO-ELASTIC SENSOR INTERFACE

MULTIPLE SOURCE/MULTIPLE DETECTOR APPROACH

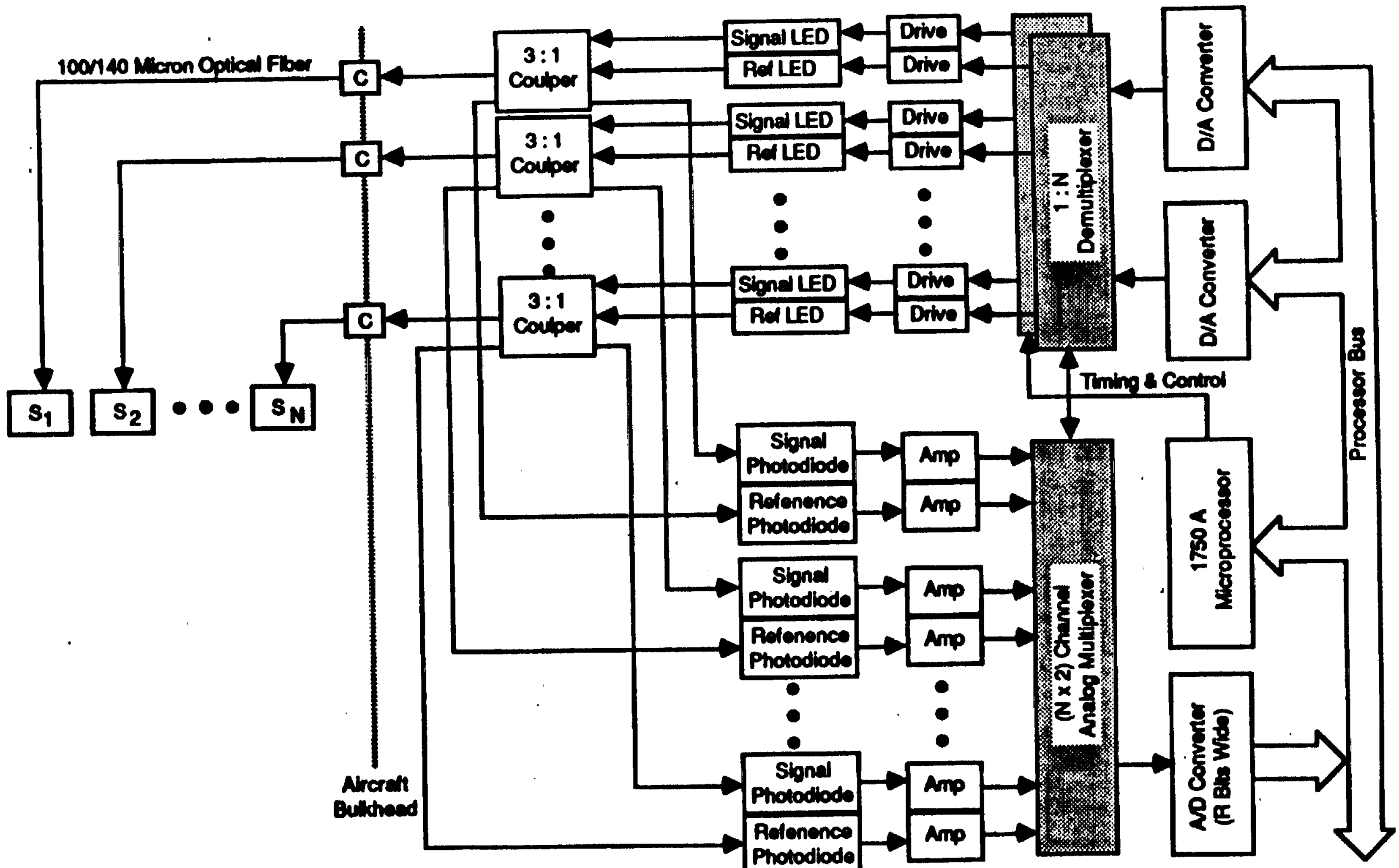
NOTE: M ≤ N (assume: N/2 Signal LEDs, N/2 Reference LEDs)



C = Fiber Optic In-Line Connector
N = Maximum Number of Sensors
R = Maximum Resolution of Each Sensor

MCDONNELL AIRCRAFT COMPANY

WDIN REFLECTIVE DIAPHRAGM SENSOR INTERFACE
MULTIPLE SOURCE/MULTIPLE DETECTOR APPROACH

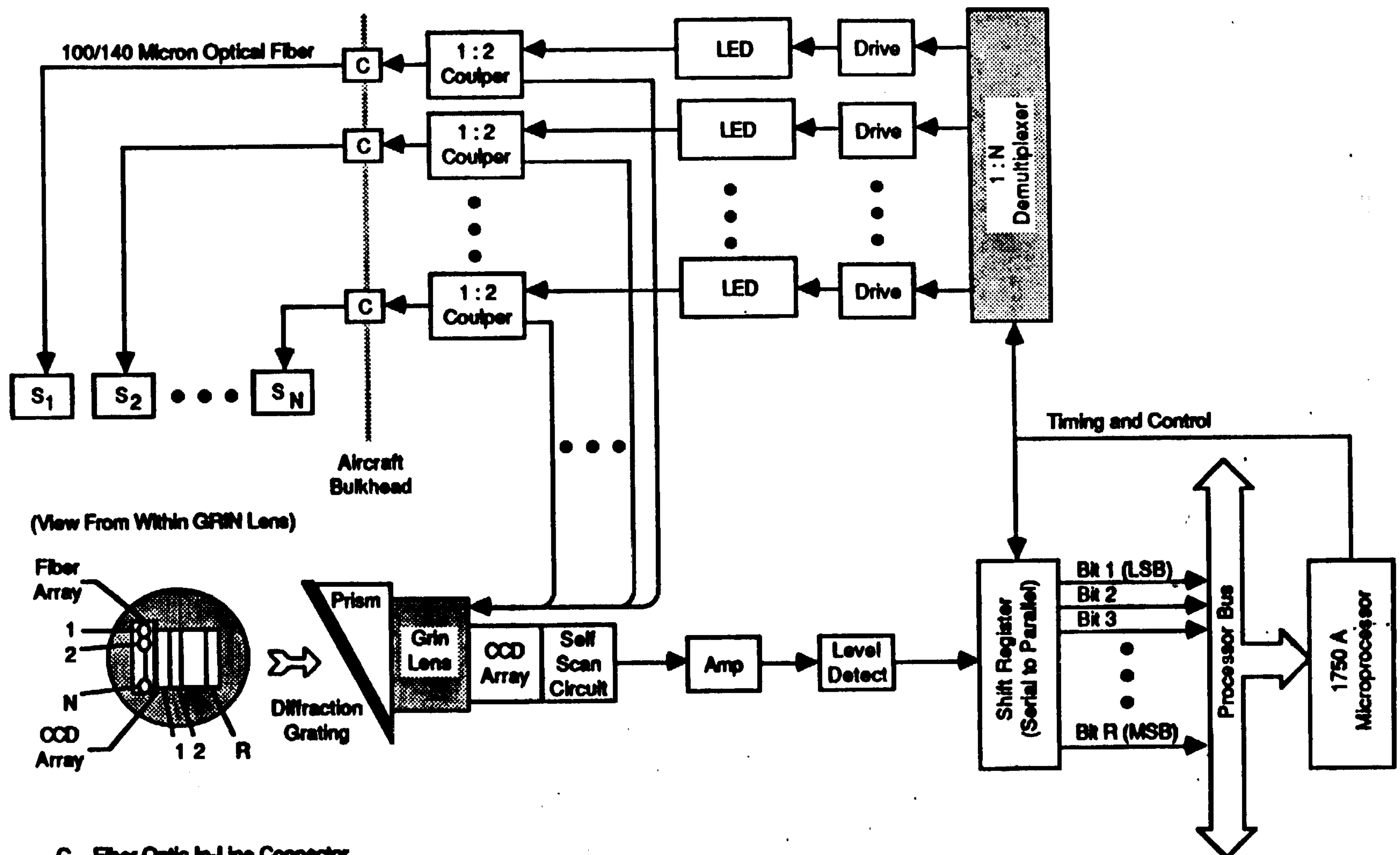


C = Fiber Optic In-Line Connector
N = Maximum Number of Sensors
R = Maximum Resolution of Each Sensor

MCDONNELL AIRCRAFT COMPANY

WDM FABRY-PEROT INTERFEROMETER INTERFACE

MULTIPLE SOURCE/SINGLE DETECTOR APPROACH

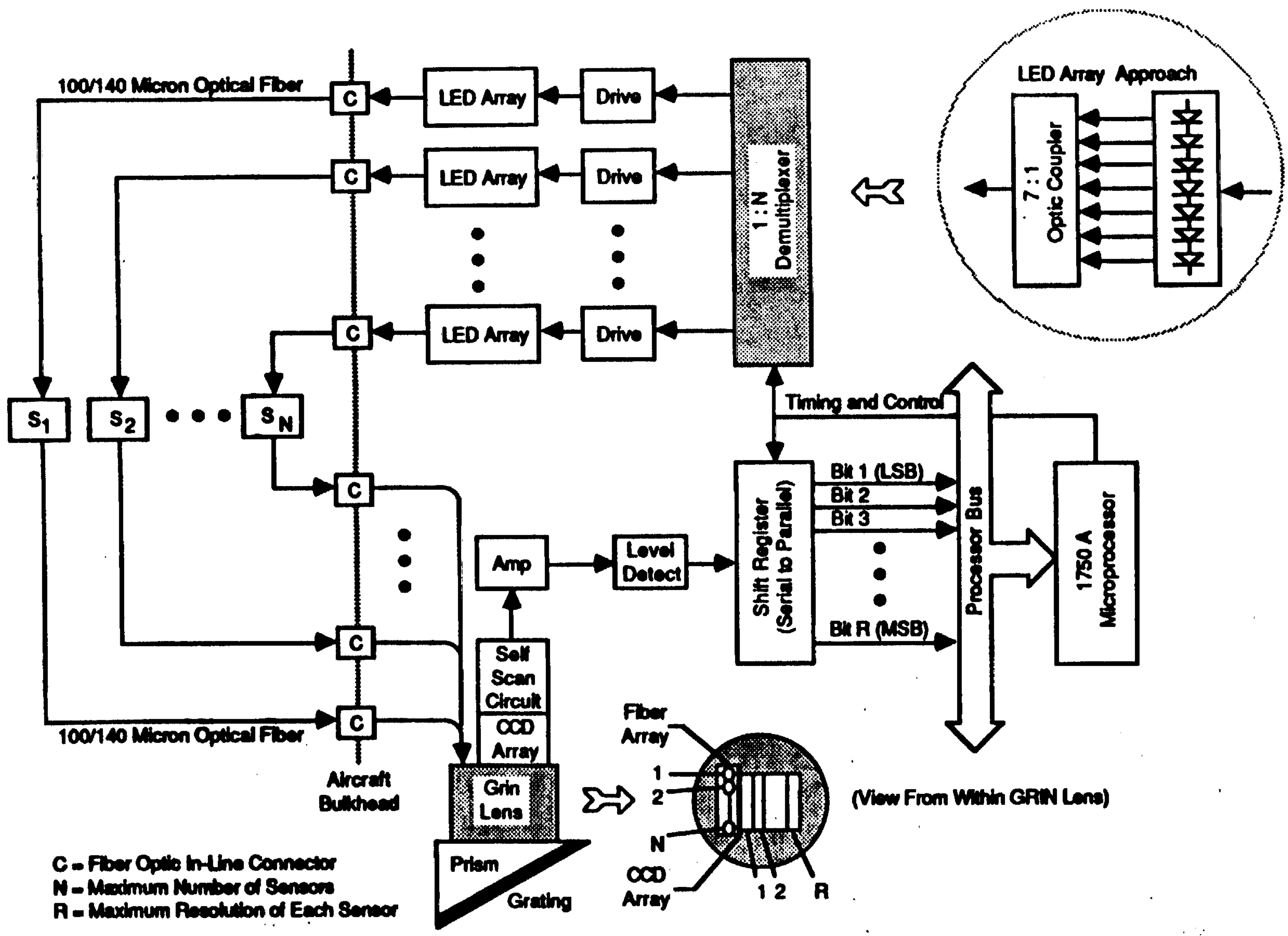


C = Fiber Optic In-Line Connector
N = Maximum Number of Sensors
R = Maximum Resolution of Each Sensor

MCDONNELL AIRCRAFT COMPANY

WDM DIGITAL OPTICAL CODE PLATE INTERFACE

MULTIPLE SOURCE/SINGLE DETECTOR APPROACH

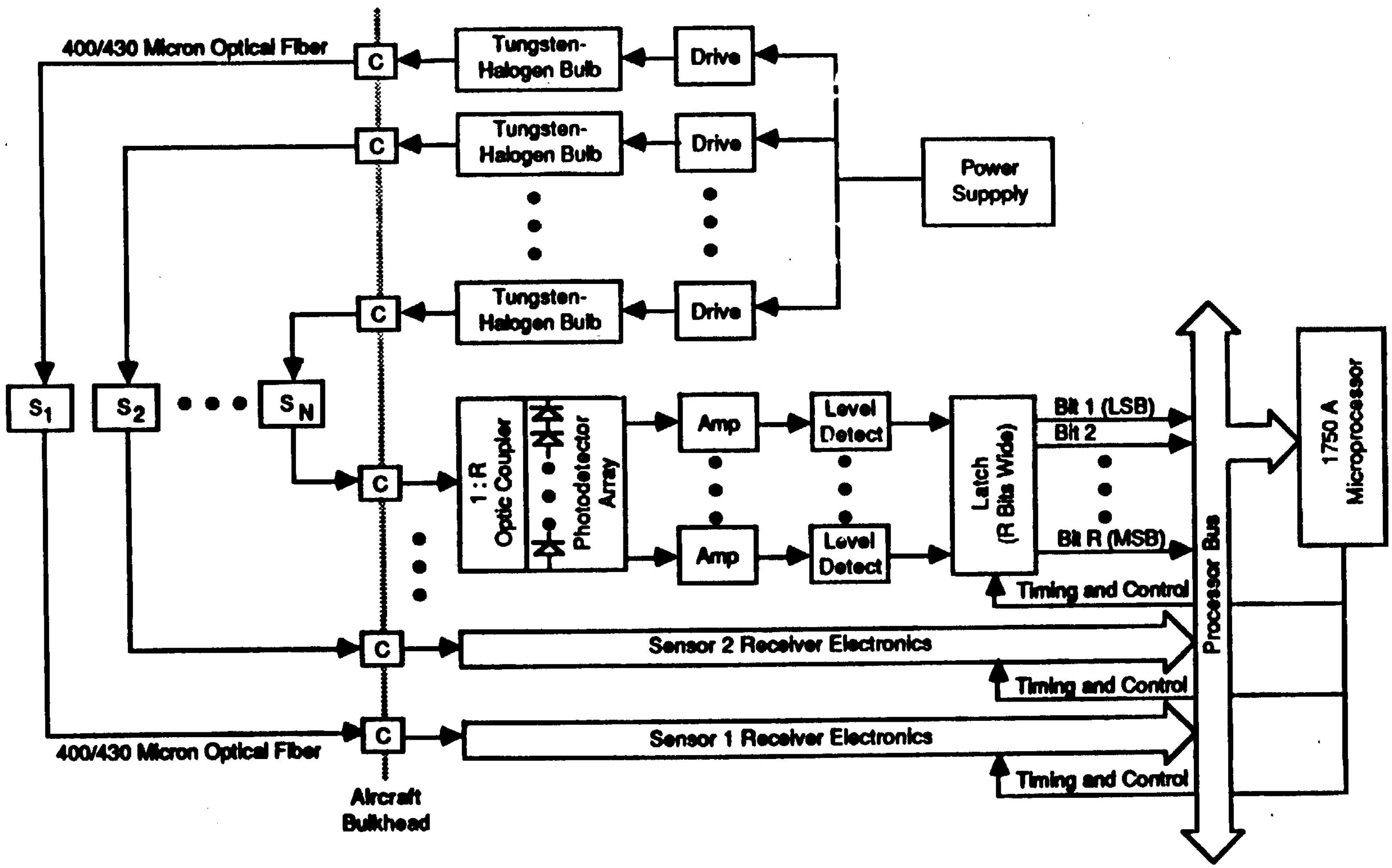


C = Fiber Optic In-Line Connector
N = Maximum Number of Sensors
R = Maximum Resolution of Each Sensor

MCDONNELL AIRCRAFT COMPANY

WDM DIGITAL OPTICAL CODE PLATE INTERFACE

MULTIPLE SOURCE/MULTIPLE DETECTOR APPROACH



C = Fiber Optic In-Line Connector
N = Maximum Number of Sensors
R = Maximum Resolution of Each Sensor

MCDONNELL AIRCRAFT COMPANY

This page intentionally left blank.

APPENDIX C

STANDARDIZED TESTS FOR FIBER OPTIC COMPONENTS

STANDARD TESTS FOR FIBER OPTIC COMPONENTS

			FOR			TEST CONDITIONS								DATA TO MEASURE (M)			
TEST NUMBER	TEST NAME	REFERENCE SPECIFICATION/ METHOD	CABLE	CONN	COUPLER	PRE-COND 48 HRS @ RT	TEMP, Deg C	TIME, HOURS	CYCLES	DIA, INCH	WEIGHT, LB	RATE	INCREMENT	OPT	CONTINUITY	MISC	COMMENTS
1'	OPT vs Temp	DOD-STD-1678/4010	X	X			-50 to +200						50 C	M			
2	Cold Bend	DOD-STD-1678/2020 III	X				-65	20		5X	3			M			
3	Burn	DAC DMS 1501	X													burn length, burn time	
4	Fluid Immersion	MIL-W-22759	X	X					*	Specify Fluids						dimensional changes	* 2 reverse bends
5	Cyclic Flexing	DOD-STD-1678/2010 II	X				RT		3000						M		
6	Fold Back	DAC	X				RT					1°/M			M	load @ discont, loop width	
7	Handling	MCAIR TM257-270	X			X	RT		2000			*			M	cycles to discontinuity	* 20 ips horiz 18 mm rotate
8	Shrinkage		X			X	-65 & RTD	5	10							length, all cable portions	
9	Tensile Strength	DOD-STD-1678/3010 II	X	X			RT	5'			70	1"/M	10#		M	load @ discontinuity	
10	Cable Twist	DOD-STD-1678/2050 II	X				RT		5000			1/S				jacket & SM deterioration	
11	Ambient Opt Pickup	RS-455-22/FOTP-22	X	X										M		optical power leakage	daylight source
12	Compressive Strength	DOD-STD-1678/2040 III	X				RT				200	1"/M		M	M	load @ 50% opt. reduction	plate, 1/2" long
13	Dynamic Cut Through	ASTM D 3032.22	X			X	RT								M	load @ discontinuity	
14	Impact	RS-455-3/FOTP-25	X	X		X	RT		1000						M	number of cycles to failure	
15	Insulation Pull-Off		X													ease of slug removal	
16	Stiffness/Springback	MIL-STD-XXX	X			X	RT									torque, angle	Paragraph 3.9.10
17	Wicking	DOD-STD-1678/6020 II	X			X	RT									weight change, dye travel	
18	Radiation Resistance	MIL-STD-883	X							3-4		10^8		M		Specify: Neutron = 1017 Steady State = 1019	

MCDONNELL AIRCRAFT COMPANY

STANDARD TESTS FOR FIBER OPTIC COMPONENTS

			FOR			TEST CONDITIONS								DATA TO MEASURE (M)			
TEST NUMBER	TEST NAME	REFERENCE SPECIFICATION/ METHOD	CABLE	CONN	COUPLER	PRE-COND 48 HRS @ RT	TEMP, Deg C	TIME, HOURS	CYCLES	DIA, INCH	WEIGHT, LB	RATE	INCREMENT	OPT	CONTINUITY	MISC	COMMENTS
19	Epoxy Bond		X													wetting adhesion	check each substrate
20	Concentricity, Topcoat	ASTM D3032.16	X													min/max coating thickness	
21	Jacket Marking	Contact, Ink Jet, Laser	X				RT	1/2								legibility - Hydoil	MIL-H-83282
			X				RT	1/2								legibility - Luboil	MIL-L-23699
			X				RT	1/2								legibility - JP-4	MIL-T-5624
																adherence per MIL-M-81531	
22	Rubbing	DAC # DXXX	X						5000		3	10/M				jacket wear thru	test against: test cable
																	#24 MIL-W-22759
																	#24 MIL-W-81381
23	Vibration - Endurance	MIL-STD-1344	X	X			RT	8		78 GRMS - Longitud				M			
							RT	8		78 GRMS - Perpend				M			
24	Static Fatigue																
25	OPT	DOD-STD-1678/6010	X	X			RT							M			modified

MCDONNELL AIRCRAFT COMPANY

STANDARD TESTS FOR FIBER OPTIC COMPONENTS

TEST NUMBER	TEST NAME	REFERENCE SPECIFICATION/ METHOD	FOR			TEST CONDITIONS								DATA TO MEASURE (M)			
			CABLE	CONN	COUPLER	PRE-COND 48 HRS @ RT	TEMP, Deg C	TIME, HOURS	CYCLES	DIA, INCH	WEIGHT, LB	RATE	INCREMENT	OPT	CONTINUITY	MISC.	COMMENTS
26	Insertion loss	EIA-455-34/FOTP-34		X										M			
27	Durability	MIL-C-38999		X					500			300/ hour		M			
28	Thermal Shock	MIL-STD-1344/1003A	X	X	X		-65 to +150	1/2	5					M			
29	Humidity Cycling	DOD-STD-1678/4030	X	X	X				10					M			10 days at 95% RH
30	Thermal/Life Aging	MIL-STD-202/108D	X	X	X		20 deg over rated temp	1000		10X	1/2			M			
31	Salt Spray	MIL-C-39029		X				216						M		wash samples, dry @38 C/12 hr	5% neutral salt
32	Vibration	MIL-STD-1344/2005 II	X	X	X				Non-Gunfire Sinusoidal					M	M	5 to 50 to 5 Hz	mounted to vibration plate per MIL-W-5088 and PS 17100 monitored for 10 nanosecond discontinuity
		MDC A3376	X	X	X				Non-Gunfire Random					M	M	50 to 2000 Hz, 21 G rms	
			X	X	X				Gunfire Sinusoidal					M	M	50 to 500 to 50 Hz	
			X	X	X				Gunfire Random					M	M	500 to 2000 Hz, 78 G rms	
33	Mechanical Shock	MIL-STD-1344/2004D	X	X	X				6 (1 shock/axis/direction)					M	M	300 G's	
34	Toxicity	MIL-C-17/180 (EC)	X								.002					concentration normalized to 100 gram burn in 1 cubic meter	
35	Indent/Flex	MCAIR TM257-232	X							1/16, 1/8, 1/4	3				M	weight dropped from 1 inch	
36	Crush	DOD-STD-1678/2040	X												M	measure load @ fiber failure	delete 1040
37	Low Temp OPT		X				- 100	1/2						M			
38	Sand & Dust	MIL-STD-202/110A	X	X				28						M		two steps @ + 63 C dust flow normal to contact faces	
39	Hydrolytic Stability	MIL-I-16923		X			+ 73	2880								testing epoxy used to captivate the fiber	

MCDONNELL AIRCRAFT COMPANY

APPENDIX D

EOA PROCUREMENT SPECIFICATIONS

TABLE OF CONTENTS

LIST OF PAGES

LIST OF ILLUSTRATIONS

LIST OF ABBREVIATIONS AND ACRONYMS

dB	Decibel
dBm	Decibel referenced to 1 milliwatt
EOA	Electro-Optic Architecture
FOCSI	Fiber Optic Control System Integration
FWHM	Full Width Half Maximum
Hz	Hertz
KHz	Kilohertz
mW	milliwatt
nm	nanometer
ns	nanosesond
TDM	Time Division Multiplex
TRD	Time Rate of Decay
WDM	Wave Division Multiplex
µW	microwatt

DEFINITION OF TERMS

Electro-Optic Architecture (EOA) - An EOA as defined herein is any equipment (hardware, software, and firmware) that supplies optical power to remote sensors and actuators, processes the modulated optical signals returned from the sensors, and produces conditioned electrical signals acceptable for use by a digital flight controller.

Leakage Power - Leakage power is the power produced by an output when that output has been commanded to be off.

Peak Power - Peak power is the maximum instantaneous power of an output produced during the active (high) portion of the duty cycle of that output.

Residual Power - Residual power is the power produced by an output during the inactive (low) portion of the duty cycle of that output.

Bit Error Rate - The rate at which the receiver commits errors when converting optical signals into digital electrical signals. Expressed in bit errors per bits received.

1.0 INTRODUCTION

The optical sensor data base developed under FOCSI II has identified over 100 currently available optical sensors based on some 20 different technology implementations. Subsequent system evaluation efforts succeeded in identifying twelve (12) "preferred" optical sensor technologies suitable for aircraft flight control and air data applications. These preferred sensor technologies are:

1) TDM Digital Optical Code Plate
2) Beam Interrupt/Pulse Count
3) Analog Gradient Filter Plate
4) Microbend Modulated
5) Reflective Diaphragm
6) Photo-Elastic
7) Absorption Edge Shift
8) Fabry-Perot Interferometer
9) WDM Digital Optical Code Plate
10) Moving Diffraction Grating
11) Phosphorescent TRD
12) Fluorescent TRD

In order to reduce the number of unique EOAs required, these preferred sensors were grouped according to sensor technology class. This resulted in the identification of three (3) EOAs to accommodate the entire range of preferred sensor technologies. Selection of the candidate EOAs was based on availability of sensor technologies which are suitable for use in an aircraft multiplexed flight control system. As shown in Figure 1-1, the candidate EOAs (not in order of preference) are:

- **Time Division Multiplexed Digital**
- **Time Division Multiplexed Analog**
- **Wave Division Multiplexed Optical Spectrum Analyzer**

	Rotary Position	Linear Position	Angular Velocity	Tachometer/ Shaft Speed	Linear Acceleration	Temperature	Pressure	Sensor Classification	EOA Classification
TDM Digital Optical Code Plate	●	●					●	TDM Digital	TDM Digital
Beam Interrupt/Pulse Count	●	●		●					
Analog Gradient Filter Plate	●	●						TDM or WDM Analog Self-Referenced Intensity Modulated	TDM Analog / WDM Optical Spectrum Analyzer
Microbend Modulated					●		●		
Reflective Diaphragm						●	●		
Photo-Elastic							●		
Absorption Edge Shift						●			
Fabry-Perot Interferometer						●	●		
WDM Digital Optical Code Plate	●	●						WDM Optical Spectrum Analyzer	
Moving Diffraction Grating							●		
Phosphorescent						●		WDM Optical Spectrum TRD	WDM Optical Spectrum Analyzer
Fluorescent						●			

= Sensors in the shaded regions are not suitable for use in an Aircraft Multiplexed Flight Control System

Figure 1-1 Flight Control Multiplexed EOA Development

2.0 EOA PROCUREMENT SPECIFICATIONS

2.1 Common EOA Characteristics - Conceptual designs for each of the three multiplexed EOAs are presented in the following paragraphs. To achieve interoperability between various sensors, the EOAs share several common hardware characteristics.

2.1.1 Sensor Multiplexing Approach - Each of the EOA designs are based upon a Multiple Source/Single Detector multiplexing approach which has been identified to be the optimal approach for remote multiplexing of optical sensors. This approach requires one optical source dedicated to each sensor. The EOA receiver is time division multiplexed among the available sensors by sequentially illuminating the individual sources dedicated to each sensor. To obtain serial data from the receiver, each of the N sensors is sampled in 1/N of the allowable integration time. To minimize system optical interconnect losses, the EOA receiver designs incorporate a non-reciprocal power combiner constructed by combining all of the sensor receive fibers into a single fiber bundle. This approach eliminates the physical splitting losses (10 log N) and excess losses associated with a fused biconical type reciprocal power combiner. Anticipated losses for this type of multiplexing will depend on the number of receive fibers and the surface area of the receiver photodetector, but can generally be assumed to be less than 3 dB. This approach is acceptable from a maintainability and integrated logistics support viewpoint only if the combiner is confined to the EOA module itself.

2.1.2 Fiber Characteristics - The following set of fiber optic transmission medium characteristics shall be met to ensure interoperability between sensors and EOAs.

Core Size:	100 micron
Cladding Size:	140 micron
Construction:	Step Index, Glass-on-Glass
Numerical Aperture:	0.29

2.1.3 Connector Characteristics - Each EOA shall have separate optical input and output connectors which shall be compatible with the following:

Contact Type:	MIL-C-38999
Contact Size:	#16 single fiber terminus

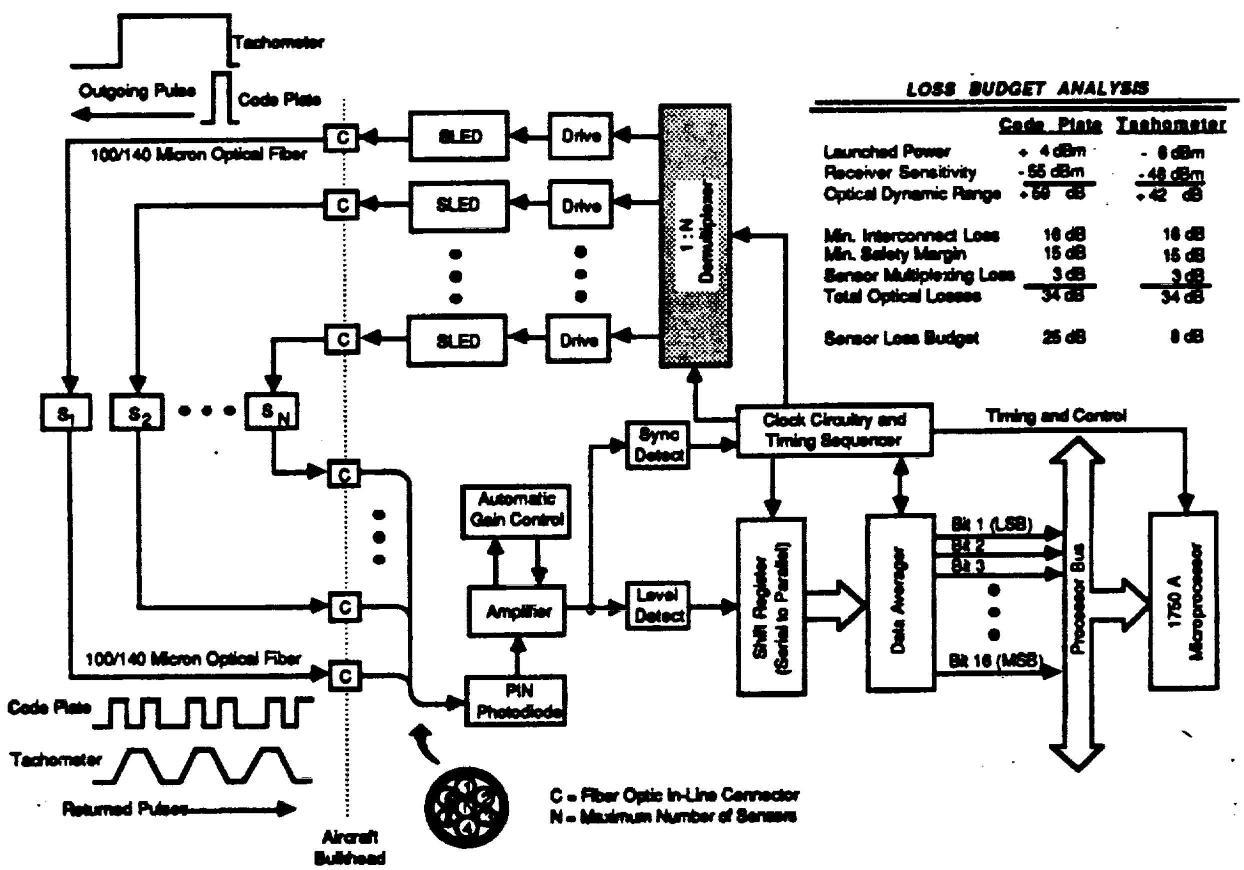
2.1.4 Optical Sensor Interface - The EOAs described in this specification are compatible with transmissive type (two fiber) optical sensors. Interconnection to reflective type (single fiber) sensors is accomplished via a passive splitter located outside of the EOA module.

2.1.5 Flight Controller Interface - The interface from the EOA to flight controller shall be MIL-STD-1553B compatible in order to maintain compatibility with existing airborne data acquisition equipment.

2.2 TDM Digital EOA Characteristics - Time Division Multiplexed Digital (TDM Digital) EOAs shall be compatible with the following types of optical sensors:

- **TDM Digital Optical Code Plate**
- **Beam Interrupt/Pulse Count (Tachometer)**

The TDM Digital EOA shall be capable of operating in either the **code plate** or **tachometer** mode. However, it is not necessary for the EOA to operate in both modes simultaneously. Whichever mode the EOA is operating in, it shall meet the specified performance requirements. A conceptual design for the TDM Digital EOA is shown in Figure 2-1.



LOSS BUDGET ANALYSIS

	Code Plate	Tachometer
Launched Power	+ 4 dBm	- 6 dBm
Receiver Sensitivity	- 55 dBm	- 48 dBm
Optical Dynamic Range	+ 59 dB	+ 42 dB
Min. Interconnect Loss	16 dB	16 dB
Min. Safety Margin	15 dB	15 dB
Sensor Multiplexing Loss	3 dB	3 dB
Total Optical Losses	34 dB	34 dB
Sensor Loss Budget	25 dB	8 dB

Figure 2-1 TDM Digital EOA

In the **code plate** mode of operation, the EOA shall produce a temporally narrow optical pulse to interrogate a network of delay lines which illuminate a digital optical code plate within the sensors. The time delay networks return a serial digital bit pattern to the EOA. A high speed optical signal conditioner within the EOA decodes these digital bit patterns to determine the sensor reading. The pulse width selected represents a compromise between the time delays achievable with fiber optic delay lines in practical geometries and the bandwidth achievable in state of the art optoelectronic transmitters and receivers. To maximize receiver sensitivity, the EOA should interrogate each sensor numerous times within the allotted sensor multiplexing limitations and use statistical averaging techniques to obtain the sensor reading. It is the responsibility of the EOA manufacturer to determine the minimum number of sampled pulses that must be averaged in order to achieve the required sensitivity and resolution within the specified sensor update rate.

In the **tachometer** mode of operation, the EOA shall produce an unmodulated (continuous wave) optical pulse to illuminate a transmissive code plate within the sensors. The rotating code plates modulate the transmitted signal and return a serial bit pattern to the EOA. An optical signal conditioner within the EOA compares the number of returned pulses against a known time reference to determine the frequency of returned pulses which indicate sensor speed. The duration of the EOA optical output pulse will vary inversely with sensor speed and must be of sufficient duration to receive an adequate number of returned pulses to accurately obtain a sensor reading. It is the responsibility of the EOA manufacturer to determine the minimum number of returned pulses that must be measured in order to achieve the required sensitivity and resolution within the specified sensor update rate.

2.2.1 <u>TDM Digital Source Requirements</u> - The EOA shall include a transmitter with the following typical characteristics as measured at the EOA output connector. The source characteristics are for the individual optical outputs within the EOA.

	Code Plate	**Tachometer**
Transmitter Peak Optical Power (high):	+4 dBm (2.5 mW)	-6 dBm (250 µW)
Transmitter Residual Power (low):	TBD	TBD
Transmitter Optical Leakage Power (off):	TBD	TBD
Transmitter Intersymbol Interference:	TBD	TBD
Transmitter Maximum RiseTime:	4 ns (10 to 90%)	4 ns (10 to 90%)
Transmitter Maximum Fall Time:	6 ns (10 to 90%)	6 ns (10 to 90%)
Transmitter Center Optical Wavelength:	850 nm	850 nm
Transmitter Nominal Pulse Width (high):	10 ns FWHM	Variable
Transmitter Nominal Bit Time (high/low):	20 ns	Variable

The TDM Digital Source must meet the above specifications over the entire thermal environment as outlined in section 3.1. The source shall be self compensating and shall not rely upon interconnection to the EOA digital receiver to achieve power stabilization. It is the responsibility of the EOA manufacturer to evaluate possible alternative implementations for source stabilization.

2.2.2 <u>TDM Digital Receiver Requirements</u> - The EOA shall incorporate a single receiver channel with an optical detector of sufficient surface area to receive signals from the specified number of multiplexed sensors. Sensor outputs will be multiplexed in time by the sequencing of the sources. Timing data is based upon a multiplexing of six optical code plate type sensors or two tachometers.

	Code Plate	**Tachometer**
Receiver Maximum Optical Power Input:	TBD	TBD
Receiver Dynamic Operating Range:	TBD	TBD
Receiver Inter-Sensor Dynamic Range:	TBD	TBD
Receiver Minimum Optical Power Input:	-55 dBm	-48 dBm
Receiver Input Maximum Rise Time:	5 ns (10 to 90%)	TBD
Receiver Input Maximum Fall Time:	7 ns (10 to 90%)	TBD
Receiver Center Wavelength	850 nm	850 nm
Receiver Nominal Bit Time:	20 ns	Variable
Receiver Maximum Bit Error Rate:	1 in 10^6 Bits	1 in 10^6 Bits
Sensor Update Rate (per sensor):	1 KHz	20 Hz

To maximize receiver sensitivity, the EOA should interrogate each sensor numerous times within the allotted sensor multiplexing limitations and use those samples to statistically achieve a greater sensitivity and resolution than would otherwise be possible with a single sample. It is a condition required by this specification that the required receiver sensitivity and resolution shall be achieved within the time allowed by the sensor update rate. The EOA shall provide the statistical processing necessary to use multiple samples to achieve the required sensitivity and resolution within the sensor update time. It is the responsibility of the EOA manufacturer to determine the minimum number of sampled pulses that must be averaged in order to achieve the required sensitivity and resolution within the specified sensor update rate.

2.3 <u>TDM Analog EOA Characteristics</u> - Time Division Multiplexed Analog (TDM Analog) EOAs shall be compatible with the following types of self-referencing analog optical intensity sensors:

- **Analog Gradient Filter Plate**
- **Microbend Modulated**
- **Reflective Diaphragm**
- **Photo-Elastic**
- **Absorption Edge Shift**

The TDM Analog EOA must be capable of multiplexing any combination of the above sensors within a single EOA. The EOA will have prior knowledge of what types of sensors are currently being multiplexed and must be capable of processing the returned signals from a known combination of these sensors. The EOA shall provide for scaling and calibration of the various sensor readings through software control. A conceptual design for the TDM Analog EOA is shown in Figure 2-2.

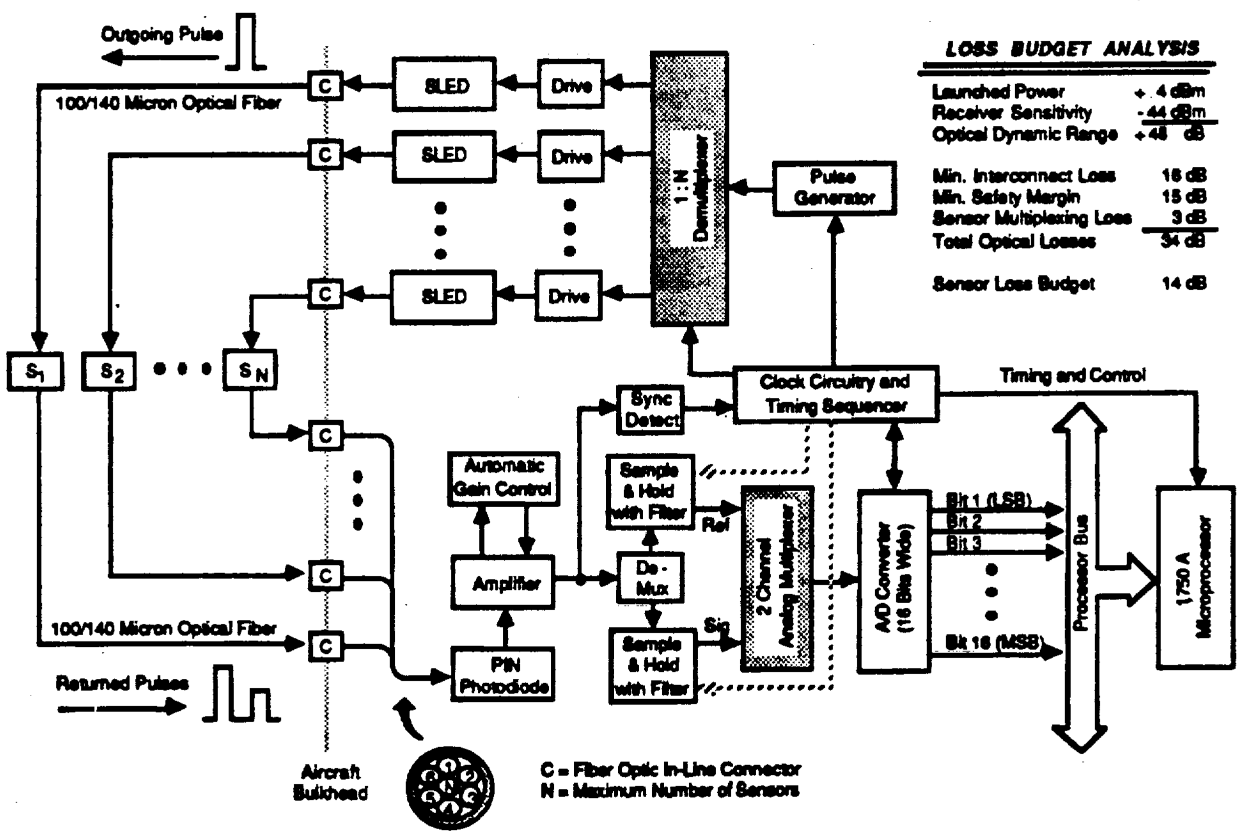


Figure 2-2 TDM Analog EOA

The EOA shall produce a temporally narrow optical pulse to interrogate a self-referenced analog intensity sensor. The sensor returns two serial optical pulses to the EOA. A high speed optical signal conditioner within the EOA decodes these pulses to determine the sensor reading. The pulse width selected represents a compromise between the time delays achievable with fiber optic delay lines in practical geometries and the bandwidth achievable in state of the art optoelectronic transmitters and receivers. To maximize receiver sensitivity, the EOA should interrogate each sensor numerous times within the allotted sensor multiplexing limitations and electronically average the readings to obtain the sensor reading. It is the responsibility of the EOA manufacturer to determine the minimum number of sampled pulses that must be averaged in order to achieve the required sensitivity and resolution within the specified sensor update rate.

2.3.1 <u>TDM Analog Source Requirements</u> - The EOA source shall have identical operating characteristics as the TDM Digital EOA source used for optical code plate sensors as outlined in section 2.2.1 above.

2.3.2 <u>TDM Analog Receiver Requirements</u> - The EOA shall incorporate a single receiver channel with an optical detector of sufficient surface area to receive signals from the specified number of multiplexed sensors. Sensor outputs will be multiplexed in time by the sequencing of the sources. Timing data is based upon a multiplexing of six analog self-referenced optical sensors.

Receiver Maximum Optical Power Input:	TBD
Receiver Operating Range:	TBD
Receiver Inter-Sensor Dynamic Range:	TBD
Receiver Minimum Optical Power Input:	-44 dBm
Receiver Input Maximum Rise Time:	5 ns (10 to 90%)
Receiver Input Maximum Fall Time:	7 ns (10 to 90%)
Receiver Center Optical Wavelength	850 nm
Receiver Nominal Bit Time:	20 ns
Sensor Update Rate (per sensor):	1 KHz

To maximize receiver sensitivity, the EOA should interrogate each sensor numerous times within the allotted sensor multiplexing limitations and use those samples to statistically achieve a greater sensitivity and resolution than would otherwise be possible with a single sample. It is a condition required by this specification that the required receiver sensitivity and resolution shall be achieved within the time allowed by the sensor update rate. The specified receiver repetition time controls the time for individual samples of the sensor. The EOA shall provide the statistical processing necessary to use multiple samples to achieve the required sensitivity and resolution within the sensor update time. It is the responsibility of the EOA manufacturer to determine the minimum number of sampled pulses that must be averaged in order to achieve the required sensitivity and resolution within the specified sensor update rate.

2.4 <u>WDM Spectrum Analyzer EOA Characteristics</u> - Wave Division Multiplexed (WDM) EOAs shall be compatible with the following general classes of optical sensors:

- **Analog Self-Referenced Intensity Sensors**
- **WDM Digital Optical Code Plates**
- **Analog Time Rate of Decay (TRD) Sensors**

The WDM EOA shall be capable of operating in either the three modes listed above. However, it is not necessary for the EOA to operate in more than one mode simultaneously. The EOA will have prior knowledge of which mode it is operating in and must be capable of processing the returned signals from any combination of multiplexed sensors within that mode. The EOA shall provide for scaling and calibration of the analog sensors through software control. Whichever mode the EOA is operating in, it shall meet the specified performance requirements. A conceptual design for the WDM EOA is shown in Figure 2-3.

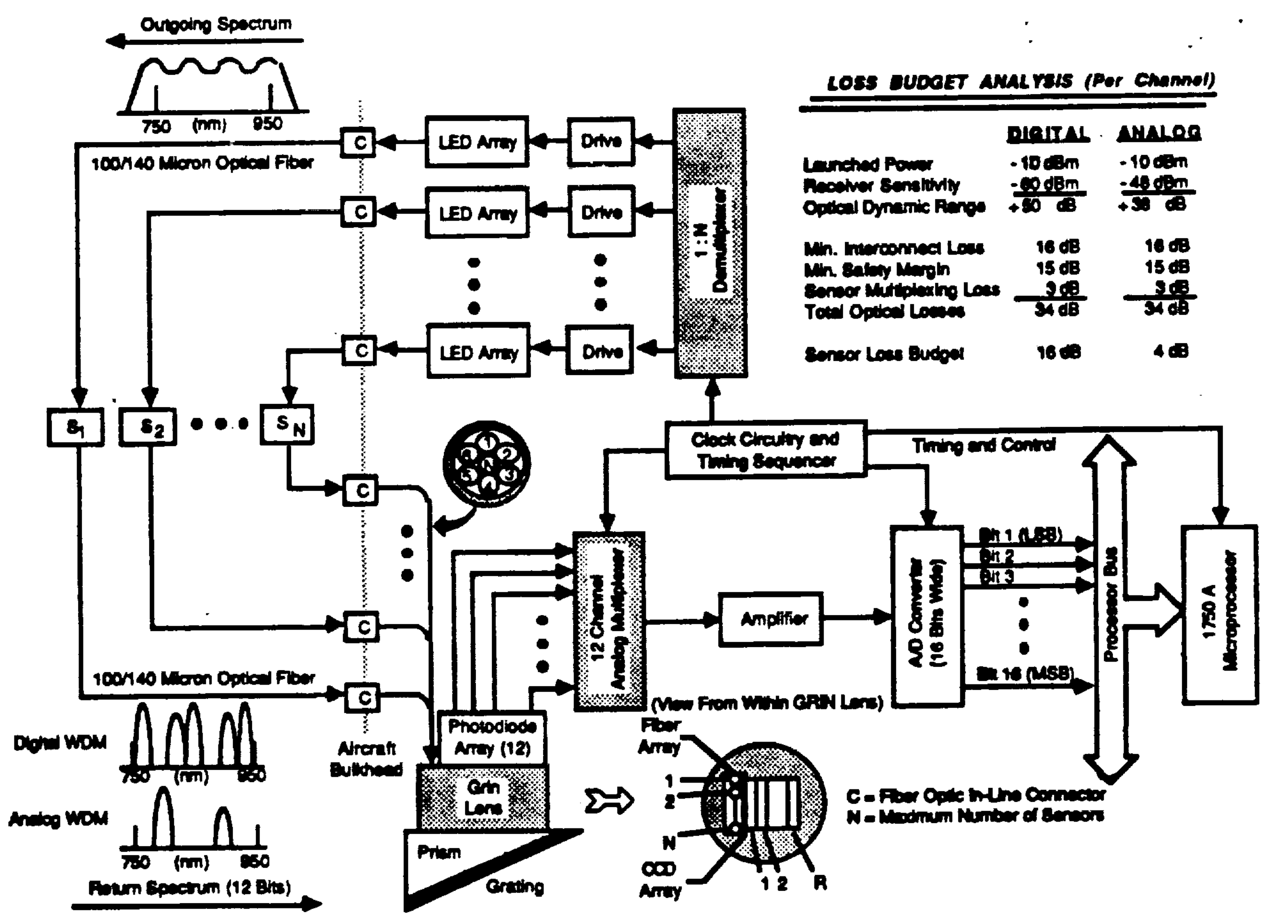


Figure 2-3 WDM Spectrum Analyzer EOA

In the **analog** mode of operation, the EOA shall produce an unmodulated (continuous wave) broadband optical pulse to illuminate a self-referenced analog intensity sensor. The sensor divides the transmitted signal into two well defined wavelength bands. The sensor allows one wavelength band to pass through relatively undisturbed (reference band) while reacting with other wavelength bands (signal band). Although a full (or partial) spectrum may be returned to the EOA, the optical spectrum analyzer would only be looking for those two bands of interest (the signal and reference). An optical spectrum analyzer in the EOA measures the relative amplitudes of the received pulses in these two returned wavelength bands to determine the sensor reading. The EOA shall be capable of resolving the returned optical spectrum into a minimum of 10 bands to maintain compatibility with digital code plate sensors. Thus, when used with analog sensors, the EOA will not use the full capability of the spectrum analyzer. It is the joint responsibility of the EOA and sensor manufacturer to identify specific parameters for the two wavelength bands. The EOA shall be compatible with the following types of **analog** sensors:

- **Analog Gradient Filter Plate**
- **Microbend Modulated**
- **Reflective Diaphragm**
- **Photo-Elastic**
- **Absorption Edge Shift**
- **Fabry-Perot Interferometer**

In the **digital** mode of operation, the EOA shall produce an unmodulated (continuous wave) broadband optical pulse to interrogate a network of optical filters which illuminate a digital code plate within the sensors. The filter networks return a wavelength encoded parallel digital bit pattern to the EOA. An optical spectrum analyzer in the EOA decodes the returned wavelength bit patterns to determine the sensor reading. The channel spacing selected represents the typical channel separation achievable with state of the art WDM components. Channel width and spacing are consistent with the 100/140 micron optical fiber size in a grating type WDM unit. The channel spacing corresponds to fiber cladding diameter while the channel width is determined by core diameter. Guard bands are employed to assure adequate channel separation over environmental and manufacturing tolerances. The EOA shall be capable of resolving the returned optical spectrum into a minimum of 10 channels. The EOA shall be compatible with the following types of **digital** sensors:

- **WDM Digital Optical Code Plate**
- **Moving Diffraction Grating**

In the **TRD** mode of operation, the EOA shall produce a temporally narrow broadband optical pulse to excite a photoluminescent sensor which emits light having an amplitude that decays over time. An optical spectrum analyzer in the EOA decodes the returned wavelength by comparing the strength of the received wavelength spectrum at different times. Because the lengthy spectral decay times (10-100 ms) normally associated with TRD sensors, these sensors cannot be multiplexed with digital or analog WDM sensors unless the TRD returned wavelength spectrum falls outside the received spectrum for the other sensors being multiplexed. Each EOA shall be able to support only one TRD sensor assuming that the returned wavelength spectrum is not in the range of returned spectrum for these sensors. The EOA shall be compatible with the following types of TRD sensors:

- **Phosphorescent TRD**
- **Fluorescent TRD**

2.4.1 WDM Source Requirements - The EOA shall include a transmitter with the following typical characteristics as measured at the EOA output connector. The source characteristics are for the individual optical outputs within the EOA.

	Analog/Digital/TRD
Transmitter Optical Power Output:	-10 dBm
Transmitter Minimum Power Density:	10 μW/nm
Transmitter Residual Power:	TBD
Transmitter Leakage Power:	TBD
Transmitter Optical Output Ripple:	3 dB across specified band
Transmitter Residual Power (low):	TBD
Transmitter Optical Leakage Power (off):	TBD
Transmitter Optical Wavelength Range:	750 - 950 nm

Because TRD sensors respond much more slowly than other WDM sensors, the source for the TRD sensor in a set need not be operated every time the sources for the WDM sensors are operated. The actual repetition rate for the TRD source shall be determined by the sensor supplier, but shall not be slower than 10 Hz.

The WDM Broadband Source must meet the above specifications over the entire thermal environment as outlined in section 3.1. The source shall be self compensating and shall not rely upon interconnection to the WDM receiver to achieve power stabilization. It is the responsibility of the EOA manufacturer to evaluate possible alternative implementations for source stabilization.

2.4.2 WDM Receiver Requirements - The WDM EOA shall incorporate a single receiver channel with optical input of sufficient area to receive signals from the specified number of multiplexed sensors. Sensor outputs will be multiplexed in time by the sequencing of the sources. Timing data is based upon a multiplexing of four WDM **Analog** or **Digital** sensors and one **TRD** sensor per receiver.

	Analog	**Digital**	**TRD**
Receiver Maximum Optical Power Input:	TBD	TBD	TBD
Receiver Operating Range:	TBD	TBD	TBD
Receiver Inter-Sensor Dynamic Range:	TBD	TBD	TBD
Receiver Cross Channel Interference:	-30 dB	-30 dB	-30 dBm
Receiver Optical Wavelength Range:	750-950 nm	750-950 nm	(note 1)
Receiver Channel Spacing:	14 nm	14 nm	N/A
Receiver Channel Width:	10 nm	10 nm	N/A
Guard Band Width:	2 nm	2 nm	N/A
Receiver Minimum Optical Power Input:	-48 dBm	-60 dBm	-48 dBm
Sensor Update Rate (per sensor)	1 KHz	1KHz	10 Hz

(1) The return wavelength for the TRD sensor must be greater than 950 nm so as not to interfere with the other sensors being multiplexed.

The WDM Spectrum Analyzer must meet the above specifications over the entire thermal environment as outlined in section 3.1. The receiver shall be self compensating and shall not rely upon interconnection to the WDM source to achieve stabilization. It is the responsibility of the EOA manufacturer to evaluate possible alternative implementations for the optical spectrum analyzer.

3.0 EOA ENVIRONMENTAL TEST SPECIFICATIONS

The purpose of these tests is to ensure that the EOA will not fail when subjected to the harsh operating environments of the aircraft. Environmental testing of pre-production EOAs for use in flight control applications shall follow the test procedures outlined below:

3.1 Thermal Environment

The EOA shall demonstrate specified performance over an ambient temperature range of -40 C to +72 C for continuous operation.

3.2 Humidity Environment

The EOA, under both operational and non-operational conditions shall be capable of operating satisfactorily during and after exposure to relative Humidities up to 100% at temperatures up to +72 C including conditions wherein condensation occurs in and on the EOA.

3.3 Vibration Environment

3.3.1 Sinusoidal Vibration Performance Testing

3.3.1.1 Resonance Survey - A resonance survey of the EOA along the first orthogonal axis shall be made. The frequency sweep shall be made slowly from 5 to 2000 Hz at 0.01 inch double amplitude or +/- 2g, whichever is less. The EOA shall be powered during this test and be required to operate satisfactorily during and after the test. Resonant points shall be noted and the response recorded and the modes of each resonance described.

3.3.1.2 Vibration Cycling - The EOA shall be vibrated along the same orthogonal axis with the frequency varying at a logarithmic rate from 5 to 2000 Hz and back in approximately 10 minutes at double amplitudes or vibratory acceleration levels indicated in Figure 3-1. The EOA shall operate during this test and shall give specified performance both during and after the test.

3.3.1.3 Resonance Dwell - The EOA shall be vibrated along the same orthogonal axis at the resonance points obtained by the the resonance survey. Vibration shall be for 5 minutes at each resonant point. The EOA shall operate during this test and shall give specified performance both during and after the test.

3.3.2 Random Vibration Performance Testing

3.3.2.1 Resonance Survey - A sinusoidal resonance survey of the EOA along the first orthogonal axis shall be made. The frequency sweep shall be made slowly from 5 to 2000 Hz at 0.01 inch double amplitude or +/- 2g, whichever is less. The EOA shall be powered during this test and be required to operate satisfactorily during and after the test. Resonant points shall be noted and the response recorded and the modes of each resonance described.

3.3.2.2 Random Vibration - The EOA shall be vibrated along the same orthogonal axis in accordance with the applicable random vibration profile indicated in figure 3-1. The duration of random vibration testing will be 10 minutes/axis. The EOA shall operate during this test and shall give specified performance both during and after the test.

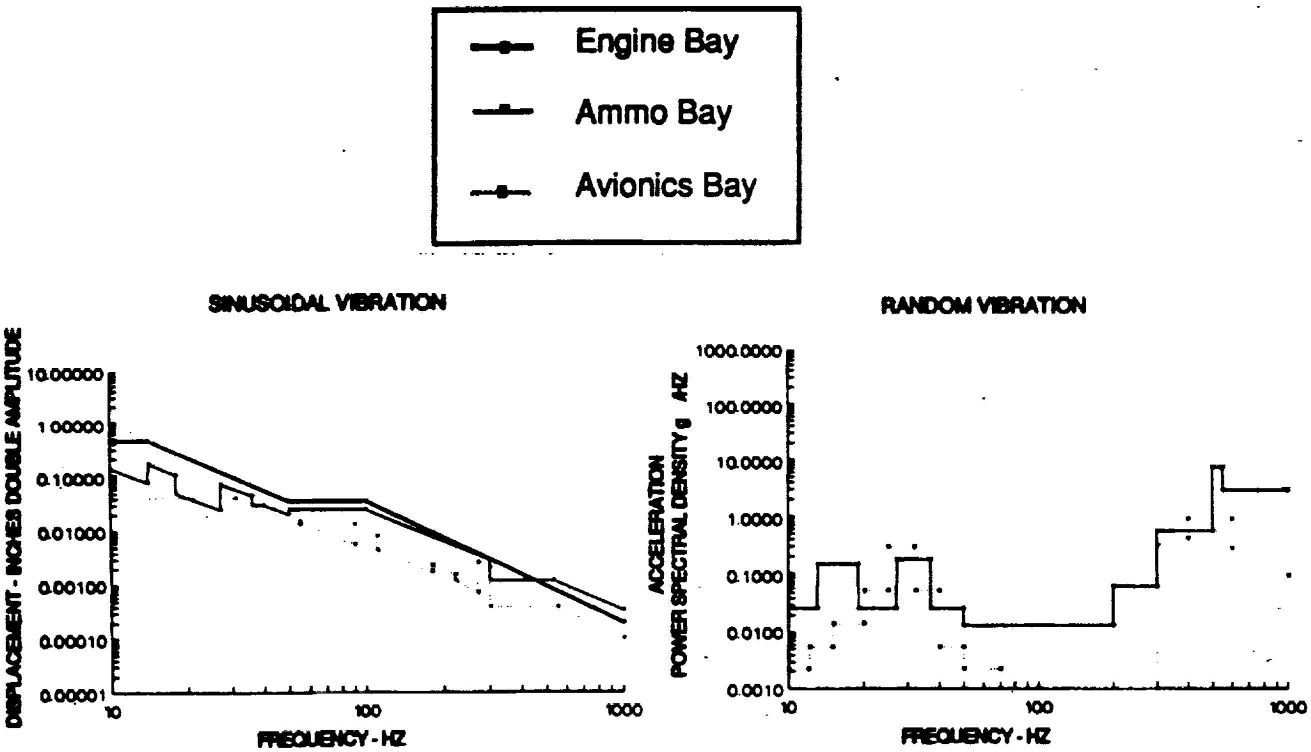


Figure 3-1 EOA Vibration Profiles by Location

3.3.3 Service Shock Performance Testing

The EOA shall be operating satisfactorily during this test. The EOA shall be subjected to 12 impacts of 15 G's peak amplitude for a duration of 11 milliseconds. After each shock, the EOA shall be thoroughly checked for any failure, and a performance check made. The shocks shall be applied in the following directions.

(a) First orthogonal axis - 2 shocks in each direction.
(b) Second orthogonal axis - 2 shocks in each direction.
(c) Third orthogonal axis - 2 shocks in each direction.

3.4 Electromagnetic Environment

The EOA modules shall be tested for radiated emissions in accordance with MIL-STD-461C section RE02, and for susceptibility to conducted emissions per MIL-STD-461C section CE03. The EOA shall be operational during these tests.