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PROXIMITY OPERATIONS CONCEPT DESIGN STUDY

TASK 6 FINAL REPORT

A. N. WILLIAMS

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TABLE OF CONTENTS

AN OPTICAL APPROACH FOR
PROXIMITY OPERATIONS COMMUNCIATIONS FOR
SPACE STATION FREEDOM

INTRODUCTION

The proximity operations communication system is a critical component in performing the missions required of the Space Station Freedom. By definition it is the system that will implement all communications within a 37 kilometer radius of the station. This encompasses all EVA activity as well as rendezvous and docking procedures in the initial phase of station deployment. It may also include links to co-orbiting platforms at growth to support the Freedom's role in NASA's new initiatives with an increased range of up to 2000 Km. Technology for communicating at Ku band (the frequency band initially selected for the prox ops communication system) is very mature, implying no significant technology challenges, but that maturity has now shown itself to be a disadvantage. Ku band has become very crowded such that NASA cannot get a primary Ku band frequency allocation for the proximity operations communication system. This means that the Freedom and its constellation could suffer severely from interferences with terrestrial as well as other space-based sources. This problem has led to the search for other alternatives for prox ops communication. One alternative, which is the subject of this report, is an optical communication system.

This report documents an effort to analyze the Space Station Freedom's mission requirements for proximity operations communication and develop an optical communications systems to meet them. An optical approach is desirable for reasons besides the interference problem: due to the inherently digital nature of a pulse position modulation (PPM) scheme, the signal processing electronics become much simpler; and the potential bandwidth is much higher than RF bandwidths, allowing a simple avenue for growth that will have a minimal impact on components ancillary to the receivers and transmitters.

The overall approach to this study was to analyze the missions and requirements and design an optical system that would minimize new development. For the most part, this approach was successful and a design of an optical communications systems consisting primarily of off-the-shelf components was produced. The one exceptional mission that will require some new development is the EVA terminal, where tracking and obscuration presents a particularly challenging problem. However, a radio at Ku or Ka band suffers from difficulties similar to an optical system. This particular mission will be treated in detail later in this report.

In summary, an optical system design was developed for the rendezvous and docking missions space station is required to support. This system is shown to be competitive with a radio frequency system in terms of size, weight, power, and development risk.

1

There are still many issues to be resolved and many elements of the Space Station Freedom Program that have not to date been firmly baselined. The following paragraphs describe the current understanding of the station's missions and system requirements. These were used as a common ground of understanding for this study.

The mission of the space station is two-fold: to support the on-going research in the various areas of the space sciences and to serve as a transportation node for NASA's new initiatives. To some extent, these are overlapping areas. In order to support the Manned Mars Mission (a new initiative), there will be a great deal of life sciences and microgravity research done on the space station. However, for the purposes of developing mission requirements, these funcitons will be considered separately.

Space Station Freedom will support on-going research in all disciplines of the space sciences. There will be both internal laboratory facilities as well as external payloads facilities. The station will provide all the basic utilities of a laboratory and the infrastructure required to transfer the information gleaned in experiments to the cognizant scientist. In addition, the internal laboratories will support man-tended experiments under the direction of a mission specialist. Examples of the Types of experiments supported internally are materials research and microgravity experiments. Examples of the types of experiments supported externally are astronomical observation and earth sending activities.

Space Station Freedom will support 21st century exploration of the solar system by providing the services of a "way station" or transportation depot as well as a "dry dock" for interplanetary space craft. The two best defined missions of this nature are the Manned Mars Mission and the Permanently Manned Lunar Colony.

To support the Manned Mars Mission, the space station will be required to support the on-orbit construction of a manned mars vehicle. This includes both vehicle assembly and logistics support. In reference to the latter, communications to a co-orbiting propellant tank farm may be required.

Support of the Permanently Manned Lunar Colony is primarily logistical in nature. The station functions as transportation node in this case, forming an interface point between the ground to low earth orbit (LEO) vehicles and the space-based non-atmospheric vehicles design to ferry personnel and materials to and from the moon.

To support these missions will require a significant amount of relatively short range communications, both to vehicles for rendezvous and docking support and to robotic elements or EVA's that support payload maintenance and vehicle construction. In addition, there may be elements of the space station constellation, such as a propellant tank farm, that require permanent, constant communications links. These are the scenarios that drive the requirements enumerated in the remainder of this report.

2

This report is divided into two major sections. The first section deals primarily with the system level requirements of the proximity operations communications and the conceptual design and interfaces of the electronics portions of the transmitter and receiver. The second section deals with the conceptional design of the optical portion of the system including optical link trades, acquisition and tracking analysis, and optical terminal design.

The remainder of this report is presented in figures with text on facing pages.

4

PART 1

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COMMUNICATION SERVICE SCHEDULING

All communication service requests are scheduled well in advance of the event. The Operations Management System (OMS), which may be either ground or station based, generates the mission time lines and determines the subsystems (C&T, DMS, GN &C, etc.) involved. Data germane to a particular subsystem is then parceled out, via the DMS network to the Operations Management Agent (OMA) resident within the control and monitor software for that subsystem. The OMA functions as the interface between the OMS and Control and Monitor (C&M) component for the core subsystem. The C&M includes Resource Manager and Fault Manager (RM & FM) elements. The RM allocates the required resources to execute the mission time line and manages resource conflicts.

For the optical C&T subsystem, the RM will mark elements as "In Use" during certain times. This will include anticipated antenna handovers. Any conflicts will be resolved by interaction between the RM, OMA, and OMS where the OMS component may include ground personnel or astronaut interface.

The trajectories and positions of the OMV and NSTS are well known to the OMS and are updated in real time. The station configuration (i.e., air locks, docking ports, antenna locations, etc.) are also well known. This implies that the initial acquisition uncertainty will be quite small. The exact angular uncertainty is 10 m rad, based on the accuracy of the Global Positioning System (GPS).

In a typical operation, an EVA or docked vehicle would be acquired at the airlock or docking port, whose position may be considered as being precisely known for the purpose of defining requirements. For vehicles entering the 37 Km proximity zone, they will be acquired upon entry.

The optical antennas must be required to provide complete coverage of the proximity zone, so that when a target passes behind an obscuration for one antenna it may be picked up by another antenna.

The system will be required to support four simultaneous links.

HIGH LEVEL MISSION PLANNING

- MISSION TIME LINES FORMULATED ON EARTH MONTHS AHEAD OF TIME

  - LONG LEAD TIME REQUIRED FOR LOGISTICS SUPPORT

  - LONG LEAD TIME REQUIRED FOR LAUNCH

  - LONG LEAD TIME REQUIRED FOR FUNDING

- TIME LINE TRANSMITTED TO SPACE STATION OPERATIONS MANAGEMENT SYSTEM (OMS)

  - ASSESSES SUBSYSTEM AVAILABILITY

  - DETERMINES RESOURCE ENVELOPES

- OMS IMPLEMENTS MISSION TIME LINE VIA SUBSYSTEMS

  - REQUESTS SUBSYSTEMS TO INITIATE SERVICES

  - SUBSYSTEMS ALLOCATE RESOURCES TO REQUESTED SERVICES

  - SUBSYSTEMS MONITOR AND CONTROL RESOURCES DURING SERVICES

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7

OPERATIONAL SCENARIOS

Two initial assumptions about the space station and its constellation upon which the communications scenarios are based are: 1) the space station, shuttle, and orbital maneuvering vehicle (OMV) all have independent links to the ground via TDRSS, and 2) all are supplied their ephemeris data by the GPS. How the space station and its related constellation elements will interface with one another until they have mutual acquisition over the dedicated links is illustrated in the figure. The space station is shown with its link to TDRSS, through which its ephemeris date is relayed to the ground. From the ground, it is exchanged with the shuttle's or OMV's position data and relayed back up. Thus the space station has an accurate value of the shuttle's state vector and vice-versa. This is the scenario assumed for both the initial station and any new elements of the growth constellation.

Critical events on the space station are scheduled well in advance. The OMS provides a mission time line to the station. This is then parceled into its elementary functions, and the space station subsystems are requested to schedule resources to execute the time line. This includes rendezvous, on-board experiments, EVA activities, etc. The subsystems then allocate their resources accordingly and manage any conflicts.

Systems on-board the space station have a very detailed knowledge of the current environmental and the environment as it may be in the future. Indeed, crew safety and mission performance could not be assured any other way. Therefore, with the possible exception of some EVA maneuvers (discussed below), uncertainties with respect to the time and position of communications targets are quite low.

The use of GPS and TDRSS allow maximum angular uncertainties to be computed for elements entering the proximity zone. For elements leaving the station, their initial position is known within a small uncertainty, since they start out docked to the station, and acquisition may begin at any given time before departure. These conditions allow for relatively straightforward acquisition procedures.

The EVA presents a particular problem for a highly directional communication system such as an optical system. Initial acquisition is relatively straightforward, since the EVA events are well scheduled and the point of egress of the astronaut is known to a high degree of accuracy. However, the link may be lost through any of several mechanisms (e.g., the astronaut bending over, or reaching, thereby bringing his arm in front of the terminal). This demands that reacquisition be robust and expeditious, which, in turn, demands that either the astronaut's position be known with a low uncertainty at all times, or a wide beam acquisition technique be developed for an optical system. It is not unreasonable to assume that the astronaut's position be known with a a high degree of accuracy, especially at initial egress from the space station. Even so, a wide field of view reacquisition procedure was developed and is presented in this report.

8

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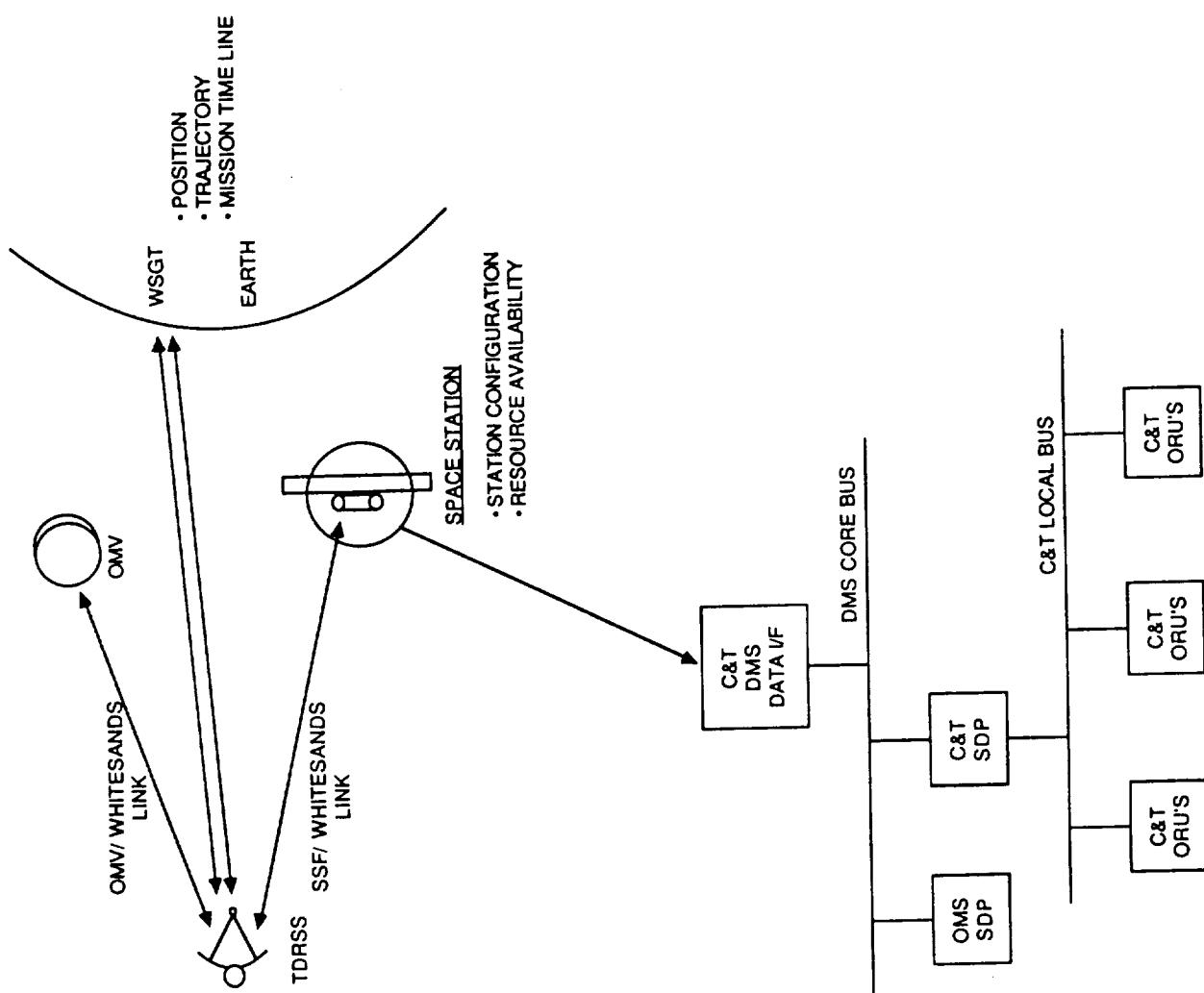
COMMUNICATIONS AND TRACKING (C&T) SYSTEM ENVIRONMENT

The proximity operations communications subsystem is a component of the space station C&T system. As such, it co-exists with the interfaces to the other C&T components. This figure illustrates the internal interfaces of the C&T System and interfaces to other elements of the space station.

The proximity operations subsystem (also called space-to-space subsystem, multiple access subsystem, and cluster communications) is the component of the C&T System that provides short range communications with various constellation elements of the space station. The proximity operations zone, from 0 to 37 Km from the space station, is itself divided into two zones; one zone from 0 to Km and the other zone from 1 to 37 Km. At growth, the proximity operation zone is planned to be extended to 2000 Km.

The C&T System has one primary internal interface to the space station. This interface is to the Data Management System (DMS). This primary interface can be further divided into at least four interfaces: the baseband communications (i.e., the local area network interface), a software interface for status and command data, a data base interface, and a man-machine interface (MMI) on the astronaut's Multi-Purpose Applications Console (MPAC) which is provided by the DMS. The C&T System side of this interface is effected by the C&T Control and Monitor (C&M) subsystem or the baseband signal processor (BSP). Telemetry and telecommand data to be communicated to or from a remote terminal will come from DMS via the BSP while command and status for the C&T System itself will come from the OMS (via the DMS network) to the C&M subsystem. The prox ops subsystem will interface to the BSP and C&M subsystem to source and sink its data.

The data interface carries the return link data from the remote terminal to the BSP. This data stream is composed of voice, video, and telemetry data. The BSP demultiplexes this data and switches it to the appropriate C&T subsystem: voice to the audio subsystem, video to the video subsystem, and telemetry to the DMS. The BSP also provided the forward link data to the receiver/transmitter (R/T) terminals. This stream is composed of voice, telecommand, and graphics data for the astronaut's heads-up display (HUD). The HUD is actually a growth requirement; however, since the bandwidth requirements on the forward link are relatively benign, it is being accommodated now.

The control and monitor interface is the interface from the various C&T subsystems to the C&M subsystem, wherein resides the responsibility for the command and control of the entire C&T System. The data transferred to and from the C&M subsystem includes commands for mode changes and Built-In-Test (BIT), as well as the return of status information. This interface will probably be either a MIL-STD 1553 bus or a IEEE 802.4 standard LAN. In order to get control and status information to and from a remote terminal, the space station will rely on the already existing path via the DMS. Control and status information will be embedded in the data stream between the DMS and the C&M controller. This provides the function of an orderwire.

C & T SYSTEM OVERVIEW
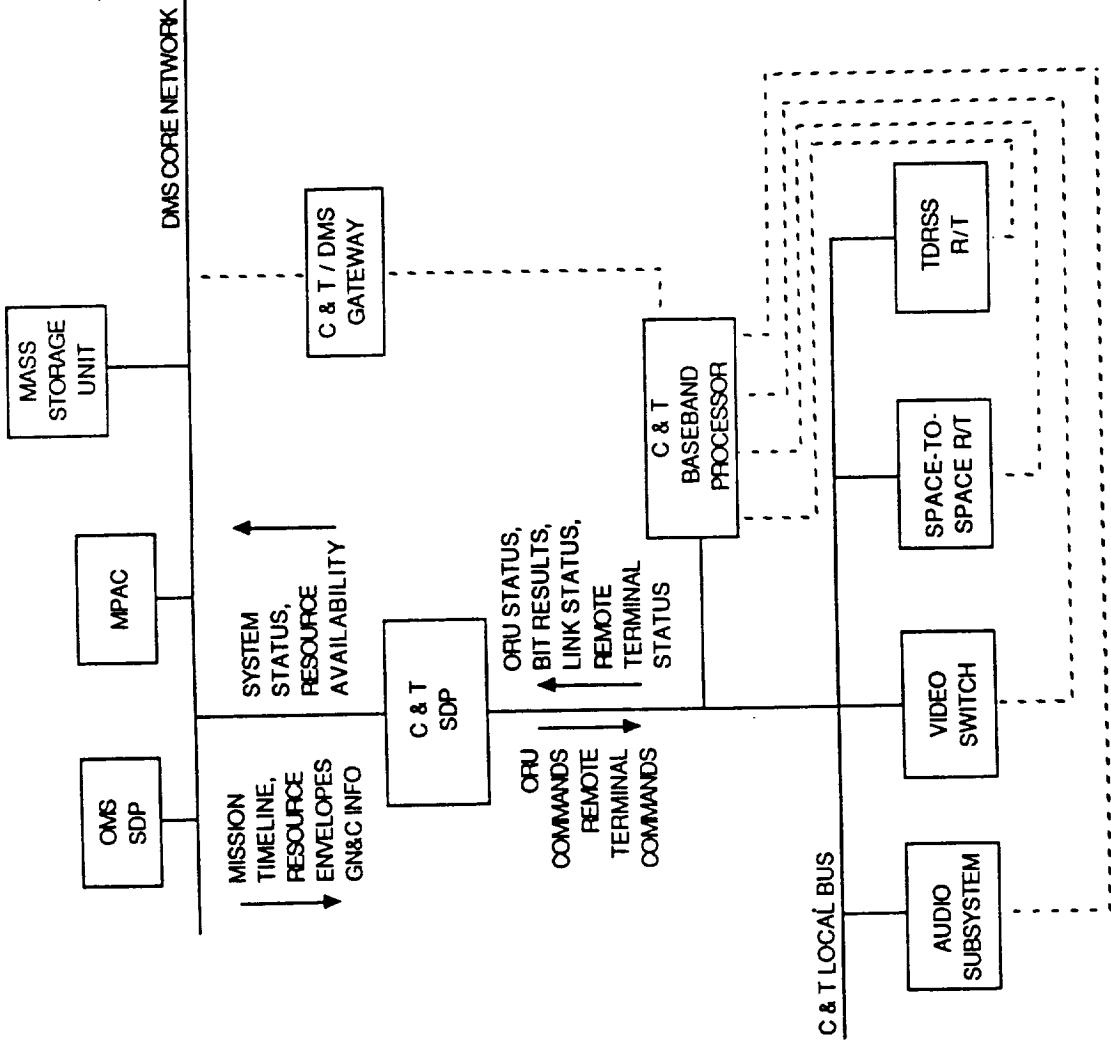
PROXIMITY OPERATIONS REQUIREMENTS

Bandwidth Requirements

In order to carry the compressed video (22 Mbps), voice, and telemetry, the return link (to the space station) will be 25 Mbps.

In order to carry the voice, telecommand, and graphics, the forward link (from the space station) will be 500 Kbps.

Range

The prox ops subsystem will communicate over a range of 0 to 37 Km with a demonstrated growth avenue to 2000 Km.

Acquisition Uncertainty

The OMV is the vehicle with the highest degree of position uncertainty due to its potential entry trajectory. There is a 10 meter axial uncertainty in its position and an angular uncertainty of 1 degree. This drives the acquisition uncertainty to approximately 20 mrad.

For the shuttle rendezvous and docking the prox ops must be able to acquire over a 10 mrad field of uncertainty within a relatively short period of time, the order of a few seconds.

For EVA, a unique situation exists in which a very large field of uncertainty is possible in the event of link loss, but with a very small field of uncertainty upon the astronaut's initial egress from the airlock. For this reason, the EVA will be required to establish and maintain two links with the space station.

VEHICLE ENTERING PROX OPS ZONE

- GPS UNCERTAINTY IN POSITION IS 10 METERS IN EACH AXIS; WORST CASE IS VEHICLE ENTERING ZONE VERTICALLY AT 9 KM

$$\sqrt{10^2 + 10^2} \doteq 15\ M$$

$$15/9000 = 1.7\ mrad$$

- BORE SIGHT ALIGNMENT UNCERTAINTY= 1 DEGREE= 17 mrad

- SPACE STATION AND VEHICLE ACQUIRE UPON ENTRY INTO ZONE AND TRACK ONE ANOTHER FROM THERE

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13

VEHICLE EXITING PROX OPS ZONE

- AT STATION, UNCERTAINTY IS ESSENTIALLY 0

- ACQUISITION WILL OCCUR BEFORE LEAVING STATION

- VEHICLE WILL BE TRACKED TO THE EDGE OF THE PROX OPS ZONE

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14

EVA SCENARIO

- AT STATION, UNCERTAINTY IS ESSENTIALLY 0

- ASTRONAUT PAUSES AT MOUTH OF AIR LOCK TO ALLOW ACQUISITION

- ASTRONAUT IS ACQUIRED AND TRACKED BY MULTIPLE TERMINALS

- IN THE EVENT OF LINK LOSS, STATE VECTOR AND DETECTOR CUBE (TO BE DESCRIBED BELOW) WILL AID REACQUISITION

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15

EYE SAFETY ANALYSIS

The following three figures detail the eye safety analysis done to insure astronaut safety during the operation of the prox ops lasercom subsystem. This analysis was done using very conservative assumptions: the astronaut is looking directly into the telescope with the naked eye (in fact, this is of course impossible since the terminals are mounted externally). The results are presented graphically on the third figure. This figure is plots of safe energy density as a function of laser power. Once the system analysis has determined the laser power requirements, the required beam diameter may be ascertained. These results show that eye safety is not an issue with the prox ops lasercom subsystem presented in this report.

EYE SAFETY ANALYSIS

- The irradiance (E_s) at range (r) can be calculated if the laser power or flux (Φ) and the beam area (A_s) are known:

$$E_s = \Phi/A_s$$

— For very close range intrabeam viewing, the laser spot size is $A_s \approx \pi a^2/4$. Then,

$$E_s = 4\Phi/\pi a^2.$$

— For longer ranges (see Figure),

$$E_s = 4\Phi/\pi(a+r\theta)^2$$

where (a) is exit beam diameter and (θ) is beam divergence.

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17

EYE SAFETY ANALYSIS (Cont'd)
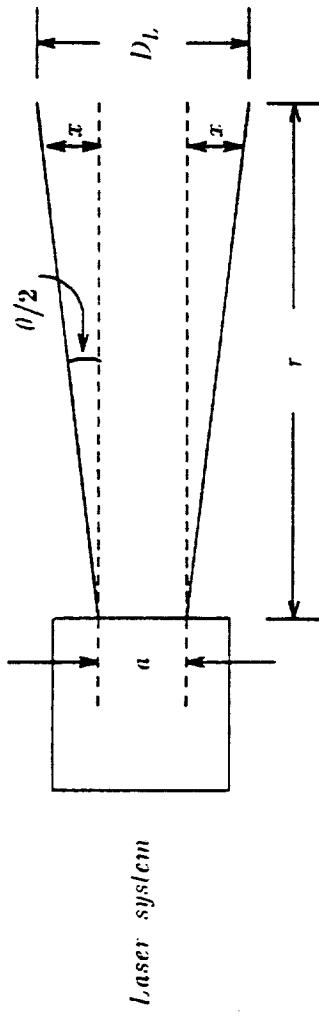
- For worst case scenario (at very close range intrabeam viewing),

$$a = \left(\frac{4\Phi}{\pi E_s} \right)^{\frac{1}{2}} = \left(\frac{4\Phi}{\pi MPE} \right)^{\frac{1}{2}}$$

where MPE represents Maximum Permissible Exposure level established by the American National Standard Institute (ANSI). Consider a $50mW$ *GaAlAs Laser* and assuming $MPE_{(GaAlAs,\ 100\ secs\ exposure\ time}$ $= 0.91\ mW/cm^2$,

$$a = \left[\frac{4(50 \times 10^{-3})}{\pi (9.1 \times 10^{-4})} \right]^{\frac{1}{2}} = 8.36\ cm$$

this means the laser system exit beam diameter must be greater than or equal to 8.36 centimeters.

EYE SAFETY ANALYSIS

wavelength = 820mm
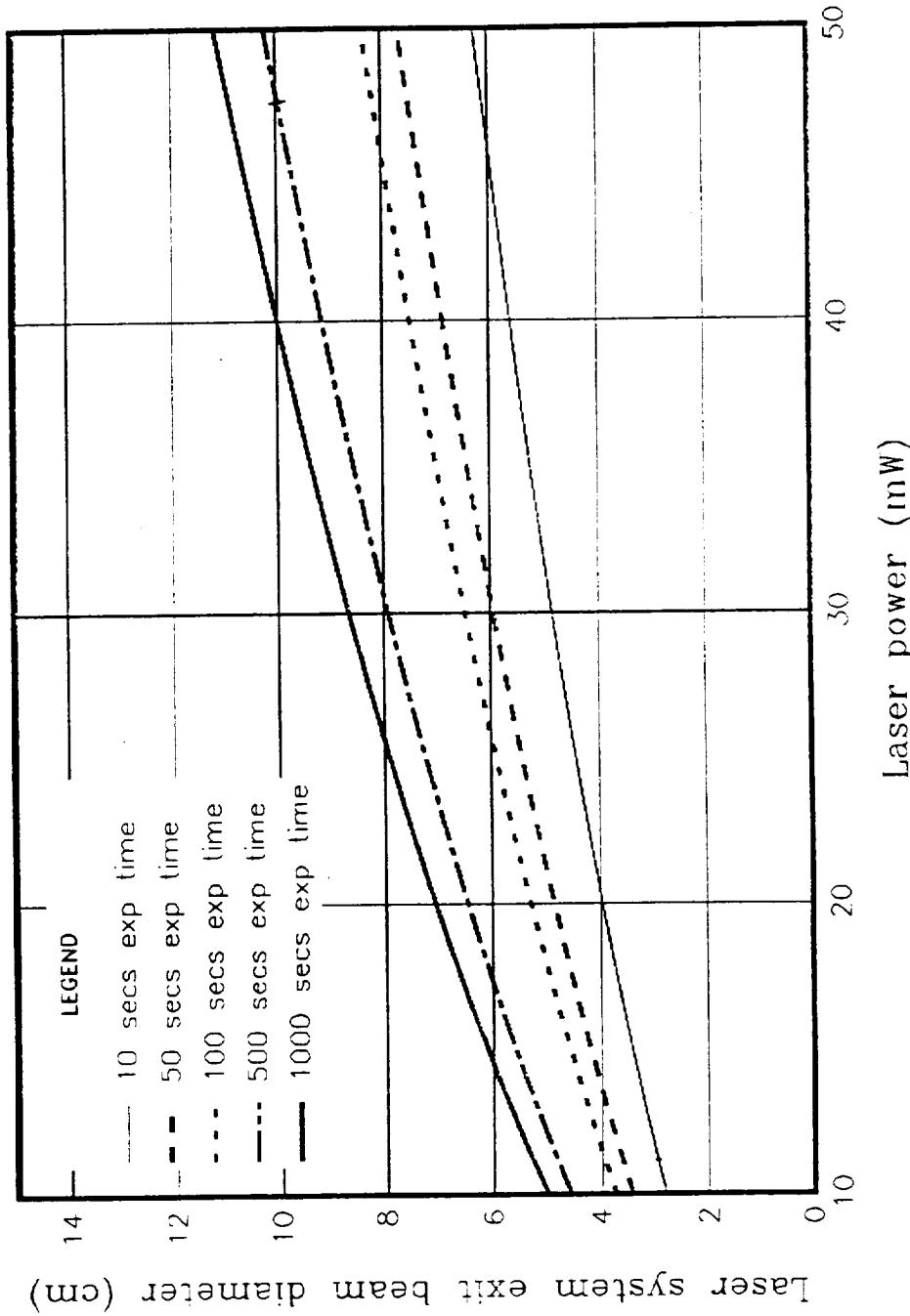
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SYSTEM DESIGN

The proximity operations communications subsystem will consist of terminals on the space station, the OMV, the shuttle, and the EVA Manned maneuvering Unit (MMU). In addition, the MMU will have a cubic sensor to assist in reacquisitions in the event of a loss of link. The overall subsystem will consist of terminals at several wavelengths. The rationale and elaboration of the use of these wavelengths will be addressed later in this report.

This will be a frame oriented communications subsystem using binary pulse position modulation (Manchester) encoding. In order to avoid link outages and facilitate tracking, a maximum-transition data stream (continuous 1,0's at the baud rate, corresponding to a string of 1's at the baseband data rate) will be transmitted between data frames. The beginning of a data stream will be delimited by two illegal BPPM transitions, first two 1's at the baud rate (50 Mbps on the return link) and then two 0's at that rate.

Following this delimiter, the header will begin. The first eight bits will represent a link identifier, assigned by the C&M subsystem following initial acquisition. The next 12 bits represent the frame length in octets. Since the orderwire is implemented using routing through the DMS, no further control fields are needed. Illegal BPPM transitions encountered before the end of frame will cause the receiver to discard the frame altogether.

20

OPTICAL PROX OPS FRAME FORMAT
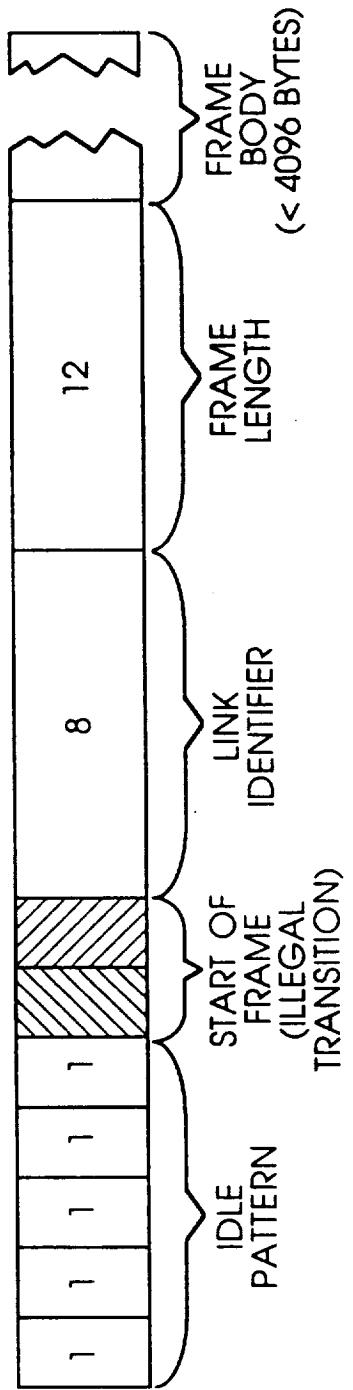
IDLE PATTERN — 1 1 1 1 1 1

START OF FRAME (ILLEGAL TRANSITION)

LINK IDENTIFIER — 8

FRAME LENGTH — 12

FRAME BODY (< 4096 BYTES)

FRAME_FORMAT

21

COMPONENT FUNCTION

There are several major functions performed by the transceiver that may be represented by different hardware components . A brief overview of the general functions of these components is presented here. More detail descriptions will follow.

The communications APD/PREAMP receives and preamplifies the incoming optical signal. Included is a sum and difference circuit that provides tracking information. This analog circuit is AC coupled to a digital receiver/decoder and clock recovery unit in parallel.

The Receiver/Decoder decodes the incoming binary pulse position modulation (BPPM) data stream, replacing a BPPM 0,1 with a data 0 and a BPPM 1,0 with a 1.

The clock recovery unit is a circuit that recovers the 50 MHz return link BPPM clock or, on the remote terminal, the 1 MHz forward link clock. This clock is used to achieve bit synchronization. As well as the 2X clock used by the decoder, a 1X clock (either 25 MHz or 500 KHz, depending on the terminal) is also made available.

At this point, just prior to entry to the DMA Controller, the receiver chain has a logic-level data stream and synchronized clock. The DMA Controller manages the contention for the Rx RAM buffer memory between the entrance of data from the communications link and the exit of data to the Baseband Signal Processor (BSP). This allows a frame to be entering at the same time one is being read out to the BSP.

The Data Formatter strips off frame control information, does error checking, and verifies that this is the correct destination for the frame.

The Data Formatter, Tx RAM Buffer, and the DMA Controller on the transmit side perform functions symmetric to their receiver counterparts.

The Data Encoder takes a logic-level 0 and converts it to a BPPM 0, 1 or a logic-level 1 and converts it to a 1,0.

The laser diode (LD) and laser diode driver comprise the remainder of the mainline communications components, and function as the transmitting components of the terminal.

The remaining three modules in this terminal form the interface between the transmitter/receiver and the remainder of the C&T System. The BSP interface is the data interface, functioning as the source and sink of the terminal's data. The Lasercom R/T Controller monitors health and status of the components and the link. Its interface to the Control and Monitor subsystem is the C&T Local Bus Interface.

SPACE STATION TRANSCEIVER BLOCK DIAGRAM

terminal overview

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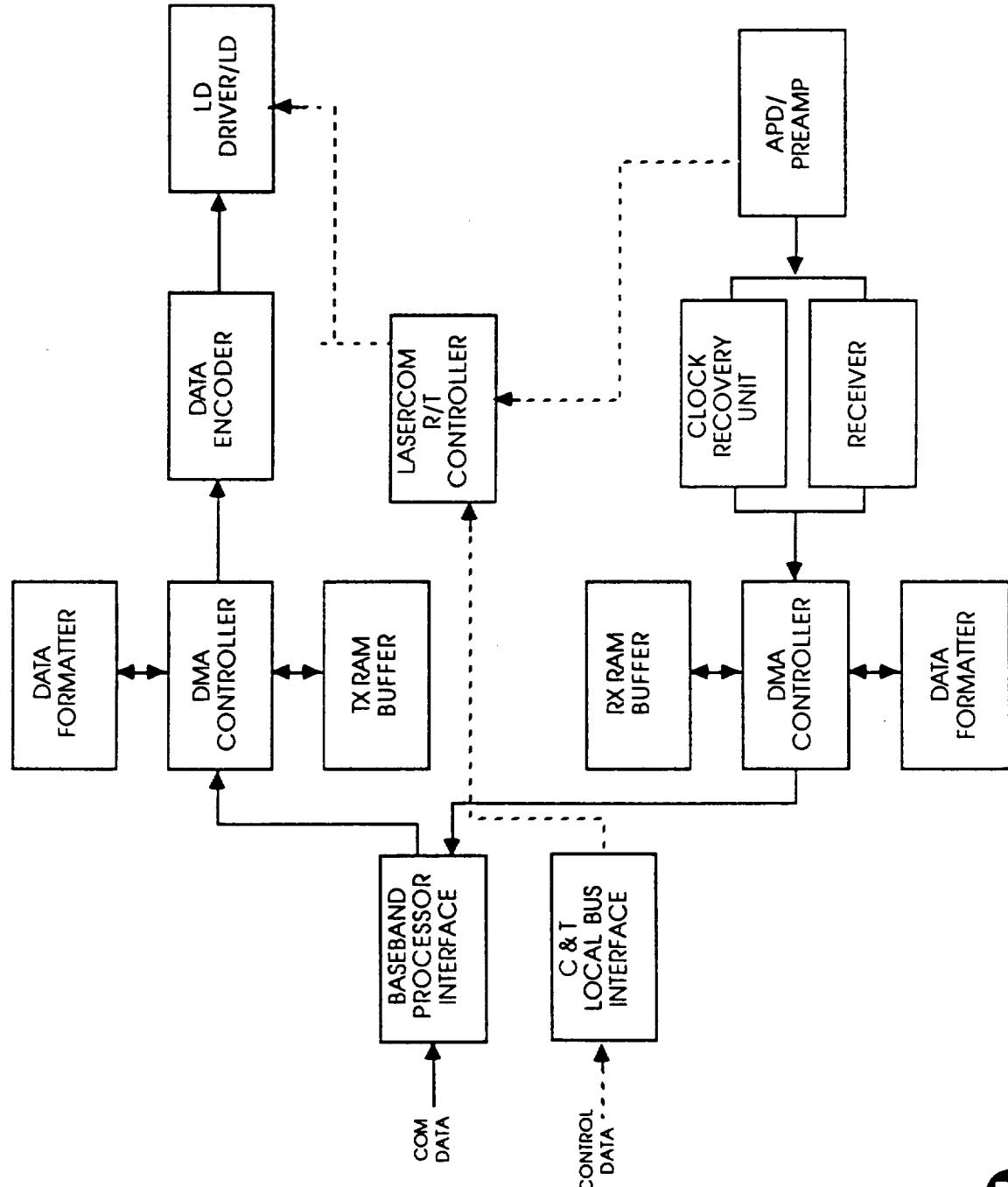
OVERALL OPERATION OF THE COMMUNICATIONS TERMINAL

Incoming optical data is received by the detector and sent to the APD/PREAMP circuit. This analog circuit boosts the strength of the input signal, shapes the waveform, and insures that the signal level is that required by the rest of the circuit. From the APD/PREAMP, the signal is then sent to the Receiver/Decoder and the Clock Recovery circuit. In the Receiver/Decoder, the start-of-frame is detected and the BPPM encoded signal is decoded into a logic-level serial bit stream. The clock is extracted from the edge transitions of the input signal by the Clock Recovery circuit. The serial bit stream then enters both the Rx DMA Controller and the Rx Data Formatter. The Rx Data Formatter stores the frame header fields and ignores the information field. The Rx DMA Controller checks for the information field and ignores the header fields. The frame header fields are saved in the Rx Data Formatter for use by the Controller. The information field is loaded into the Rx RAM Buffer 16 bits at a time by the Rx DMA Controller. The Rx RAM Buffer is also accessible to the Baseband Processor Interface for reading the received information field and transferring it to the BSP.

The operation of the transceiver during data transmission is similar to the sequence described above, but in reverse. The Baseband Processor Interface writes to the Tx RAM Buffer through the Tx DMA Controller. The frame header to be sent is then assembled by the Tx Data Formatter one field at a time. The information field is constructed by the Tx DMA Controller by reading from the Tx RAM Buffer 16 bits at a time. The frame fields are serially shifted into the Data Encoder. In the Data Encoder, the serial bit stream is BPPM encoded and sent to the LD Driver/LD. The LD Driver/LD converts the BPPM encoded bit stream into optical signals for transmission through space.

The C&T Local Bus Interface permits the transfer of control signals to and from the Lasercom R/T Controller. The Lasercom R/T Controller monitors the link status and BIT in the hardware and makes this information available to the C&M subsystem.

More detailed descriptions of the operation of the communication transceiver follow. The logic diagrams are not meant to be definitive netlist, but to convey the basic logic associated with the functions. Appropriate hardware rules are used to determine the actual gate counts from these preliminary logic diagrams and to determine the size, weight, and power (SWAP) requirements.

SPACE STATION TRANSCEIVER BLOCK DIAGRAM

terminal overview
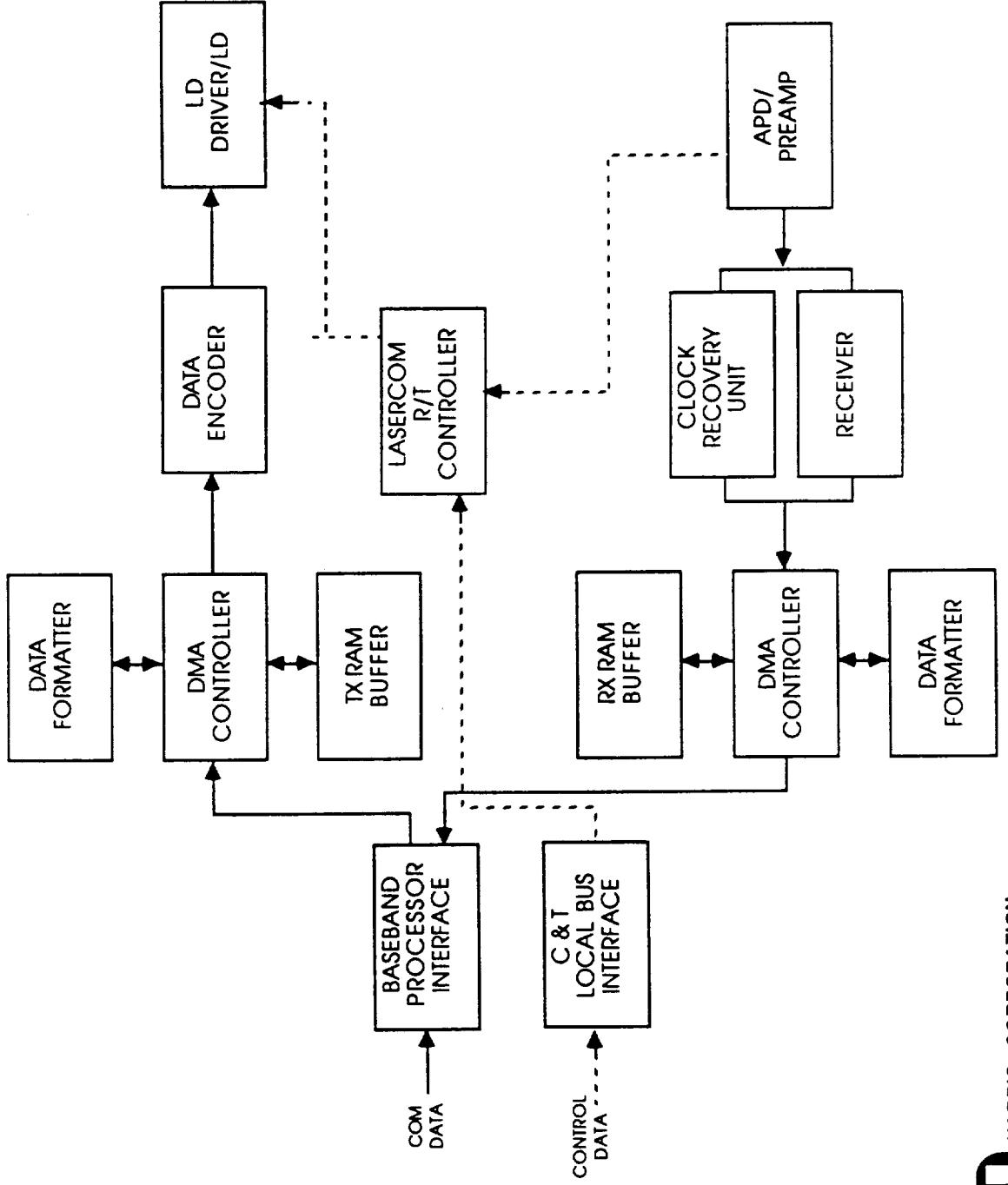
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RECEIVER/DECODER

Several different options were considered for the Receiver/Decoder design. From the choices of purely digital detection and analog maximum likehood detection, a hybrid approach was developed that provided the minimum bit error rate of the matched filter with the ease of implementation of a digital threshold approach.

This circuit interfaces with the APD/PREAMP and receives from it the reconstructed BPPM electrical signal. For the purposes of this discussion, the 25 Mbps signal will be assumed; the numbers may be scaled appropriately for the 500 Kbps link. The low-pass filter is designed to roll sharply above 25 MHz, utilizing a multipole low-pass filter, thereby passing the base 50 MBPS BPPM signal and eliminating unwanted harmonics.

A standard lumped element delay line is placed in parallel to retard the signal for 20 nanoseconds, one-half the period. The op amp therefore is comparing the waveform at two, 20 ns spaced intervals. The output of this element at three-quarters of the way through the 40 ns cycle is the NRZ data representation. The upper AND gate, which samples this data at the correct clock time, produces the logic level signal, which is then latched. The buffer and remaining circuit detects illegal BPPM transitions.

26

HYBRID RECEIVER

NRZ DATA OUT

ILLEGAL TRANSITION

START OF FRAME

CLOCK RECOVERY

50 MHz

D D FF

BUF-FER

20 Ns DELAY

LPF

Σ

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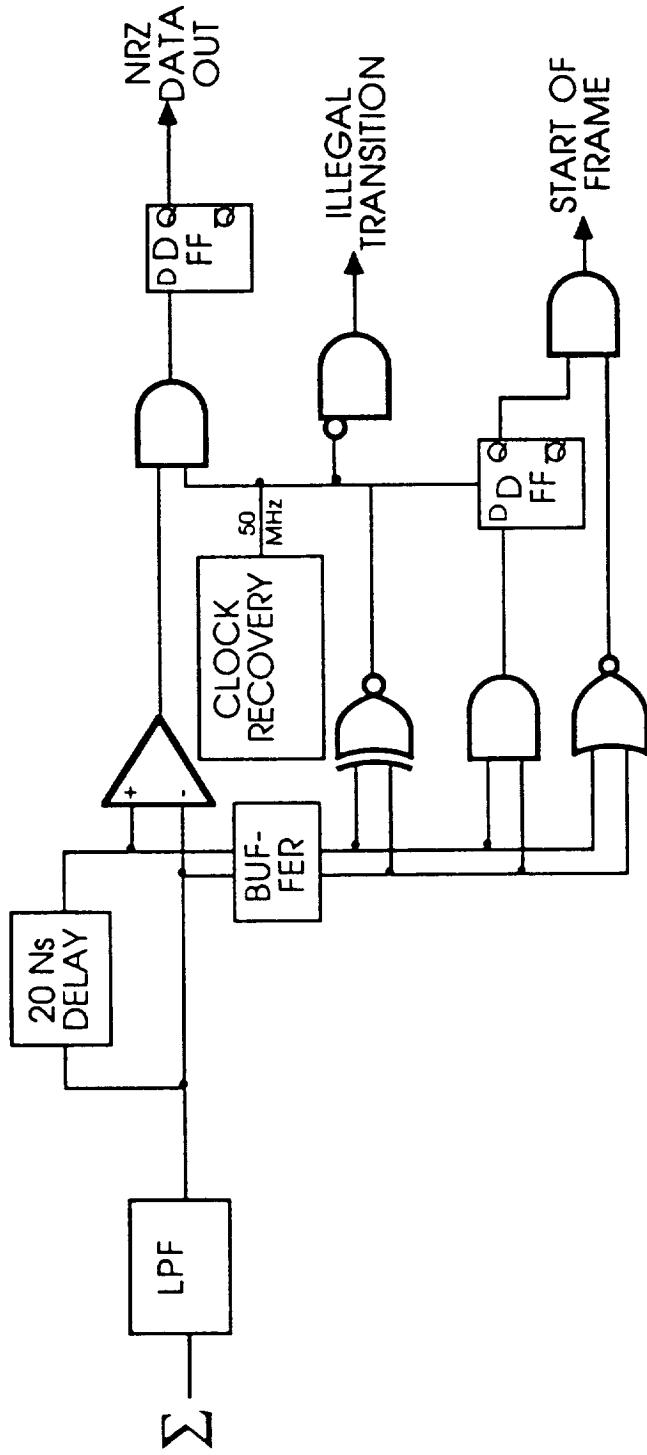
CLOCK RECOVERY UNIT

The function of the Clock Recovery Unit is to provide a 25 MHz clock to the receive chain that is synchronized to the data stream. This is accomplished by detecting the transitions on the BPPM data stream, which has a strong 50 MHz harmonic. This is filtered to produce the synchronized clock. A peak detector uses the total energy to validate the clock.

CLOCK RECOVERY UNIT

Σ DATA FROM DETECTOR → TRANSITION DETECTOR → 50 MHz BANDPASS FILTER → 50 MHz CLOCK OUTPUT

PEAK DETECTOR → LOW PASS FILTER → CLOCK OK OUTPUT

REFERENCE VOLTAGE

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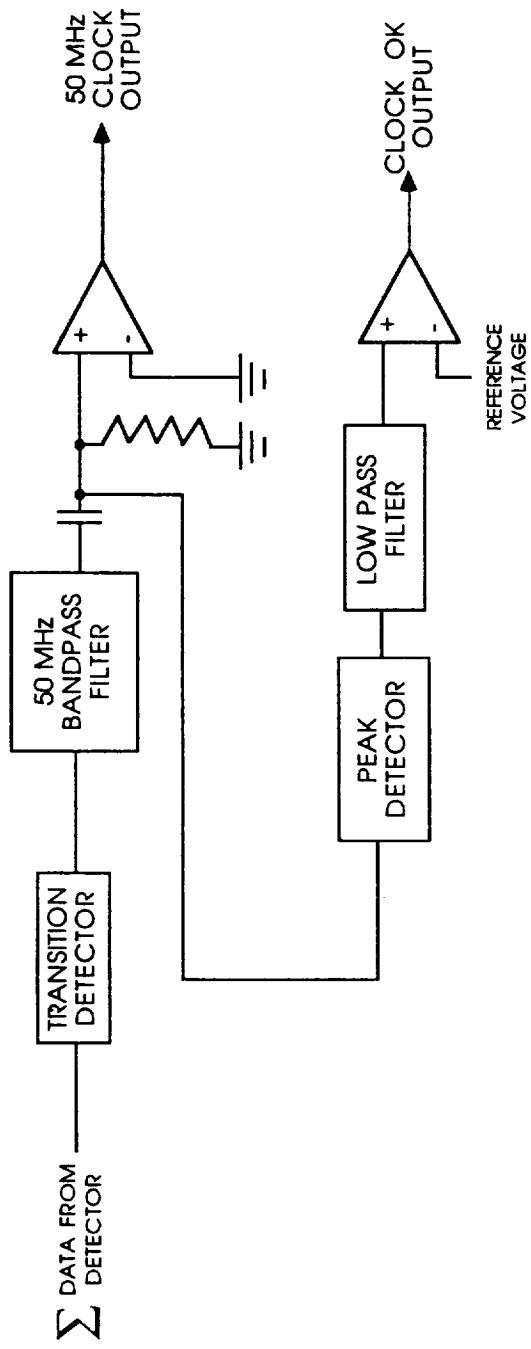
RX DATA FORMATTER

The Rx Data Formatter separates the header fields of the incoming data from the information field. When the Rx Data Formatter encounters the information field, it asserts a signal, INFO_FIELD. Field separation is accomplished using a bit counter. For the purpose of this discussion, the first 16 bits counted after the start of frame are assumed to be the DEST_ADR field. The next 16 bits are assumed to be the FRAME_CONTROL field. The third sequence of 16 bits is assumed to be the FRAME_LENGTH field. The FRAME_LENGTH defines the length of the information field.

Each field is stored in a separate shift register. All shift registers initially shift in the incoming data. As the field boundaries are detected (bits 15, 31, and 47), the SHIFT_ENABLE signal to the corresponding shift register is disabled. The data for that field is thus preserved.

After the FRAME_LENGTH field has been saved, the Rx Data Formatter resets the bit counter and asserts the signal, INFO_FIELD. This signal is used by the Rx DMA Controller to initiate the storing of the information field in RAM. The Rx DMA Controller will continue to do RAM stores as long as INFO_FIELD remains active. INFO_FIELD remains active until Rx Data Formatter detects the end of the information field. Since the bit counter was reset before the information field started, the end of the field is detected when the counter value equals the value of the FRAME_LENGTH. At this point, the Rx Data Formatter also possesses the frame check logic to detect data errors. When no errors are detected, the signal FCS_OK is asserted.

Rx DATA FORMATTER

data_formatter
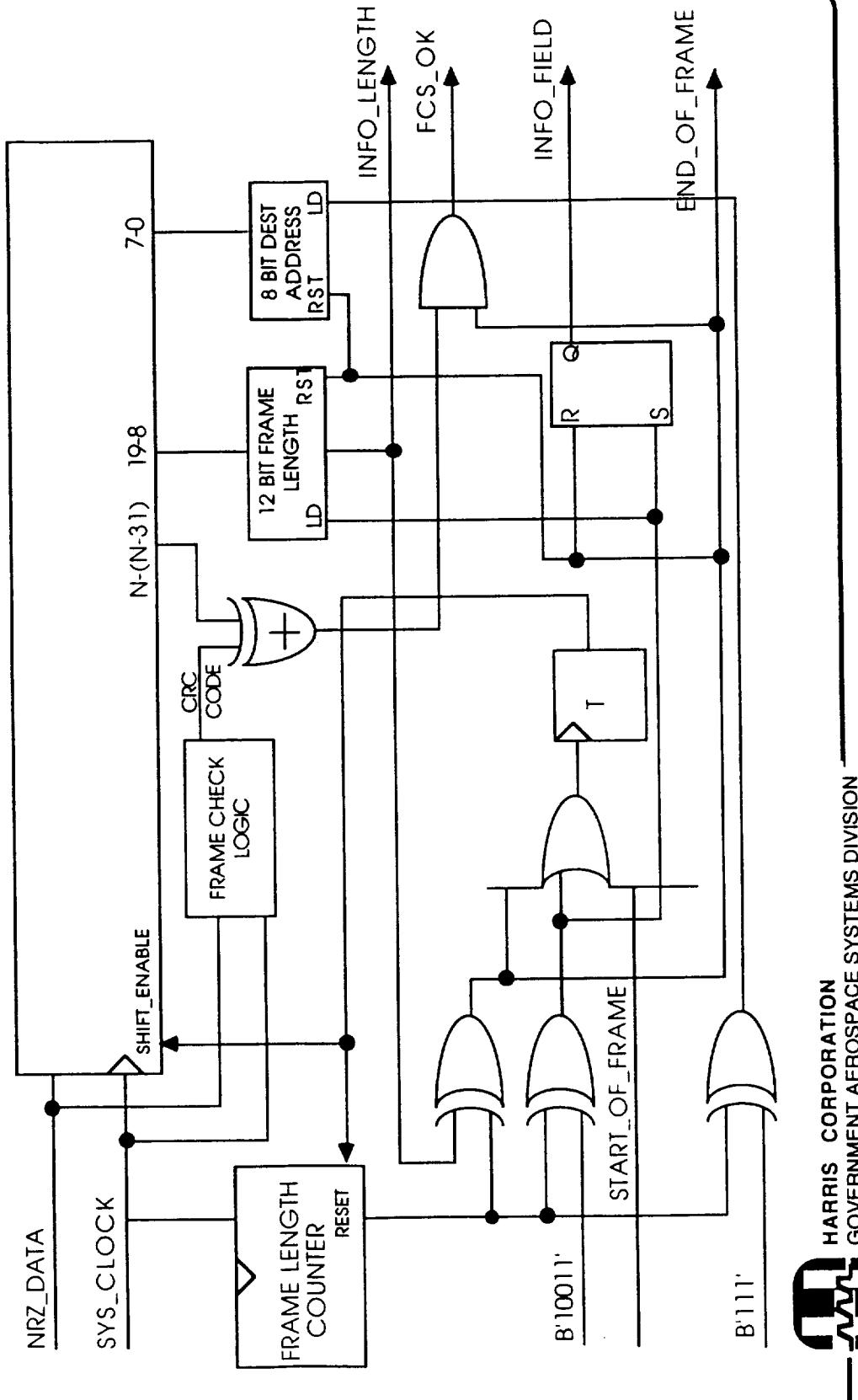
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RX DMA CONTROLLER

The Rx DMA Controller provides access to the Rx RAM Buffer. Two resources compete for access to the buffer. These are the Receiver, which seeks to store the information field and the Baseband Processor Interface which seeks to read the received information field. The Rx RAM Buffer is designed such that both the read and write may happen simultaneously.

During the reception of a frame from the Receiver, the Rx DMA Controller waits for a signal, INFO_FIELD. This signal is active while the information field of the frame is being received. This signal comes from the Rx Data Formatter which separates the various frame fields. While the information field is being received, the Rx DMA Controller stores the data, 16 bits at a time into the Rx RAM Buffer. When the signal INFO_FIELD becomes inactive, the RAM stores stop.

When the Baseband Processor Interface needs to read stored data, it issues a BPI_DATA_REQUEST. The Rx DMA Controller then provides the read address from a counter. The stored data is accessed in the same sequence in which it arrived. The BPI_DATA_REQUEST does not interfere with the data currently being stored. The reads and writes are occurring on separate banks of the RAM.

DMA CONTROLLER

BPI_DATA_REQUEST

SYS_CLK

NRZ DATA

INFO_FIELD

RX_RAM_READ_ADR

RX_RAM_WRITE_ADR

RX_RAM_DATA

LOAD_RAM_BYTE

READ_ADDRESS_POINTER
(16-BIT WIDE COUNTER)

WRITE_ADDRESS_POINTER
(16-BIT WIDE COUNTER)

INFO SHIFT REGISTER
(16-BITS WIDE)

SERIAL_IN

DATA_OUT

RAM DATA BUFFER
(16-BITS WIDE)

LOAD_ENABLE

DFF

4-BIT COUNTER

RESET

B'1111'

DFF
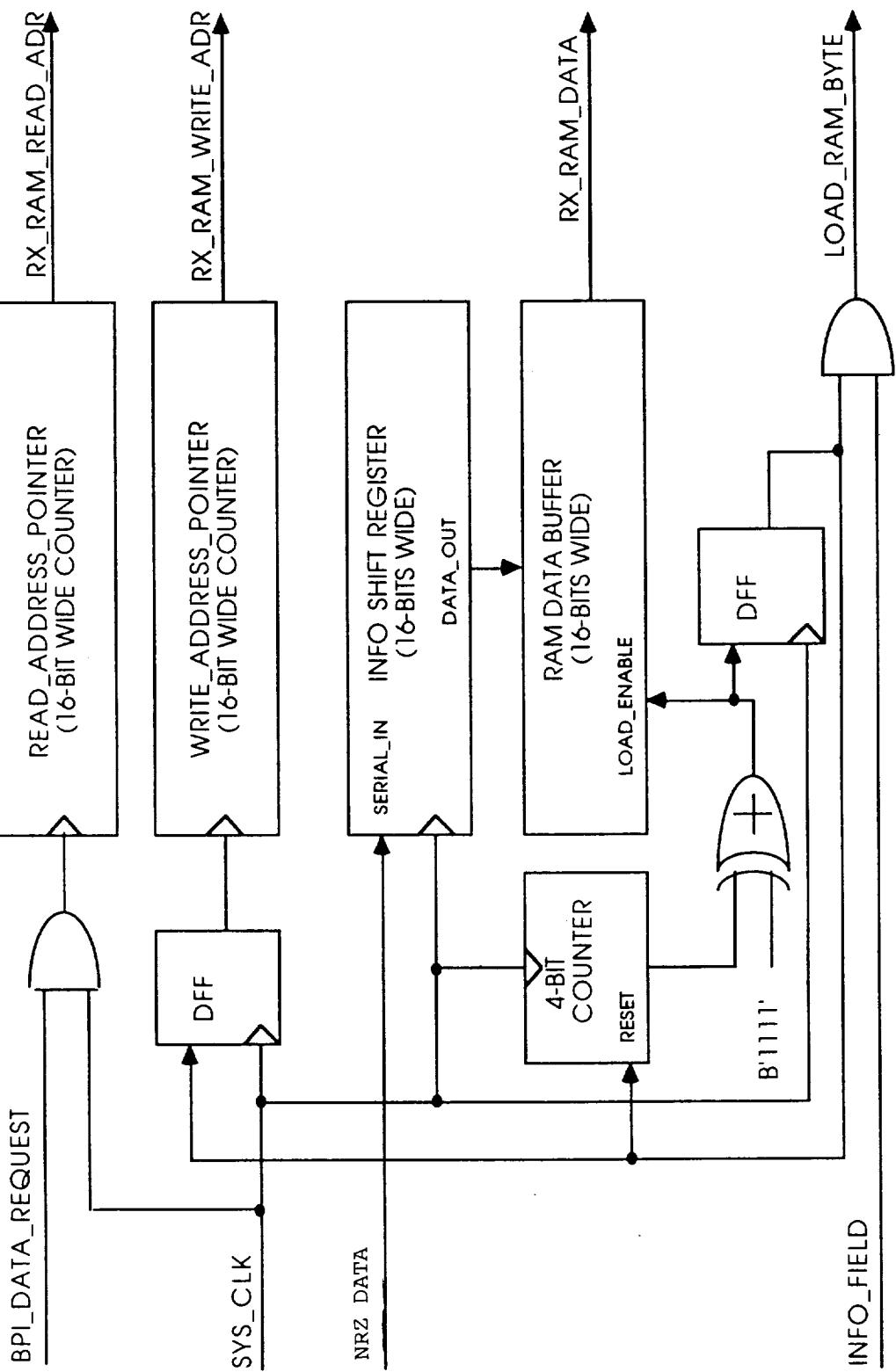
dma_controller

RX RAM BUFFER

The Rx RAM Buffer stores the received information fields until they can be read by the Baseband Processor Interface. The Rx RAM Buffer is divided into two banks. While one bank is being written to by the Receiver, the other bank is being read by the Baseband Processor Interface. A T flip flop controls the multiplexing between the two banks. Each time the INFO_FIELD signal is asserted, the T flip flop changes state. The Q and Qbar outputs of the T flip plop are made available to the select lines for the address multiplexors and the READbar/WRITE inputs to the RAMs. The multiplexing is designed such that one multiplexor selects the read address with the READbar/WRITE logically false. The other multiplexor selects the write address with READbar/WRITE logically true. Upon receipt of a newly-active INFO_FIELD signal, the T flip flop changes state and the read/write operations are "swapped". The RX_DATA_OUT is made available to the Baseband Processor Interface.

RX RAM BUFFER

RX_DATA_OUT

RX_RAM
(n x 16)

DATA_IN
ADDRESS
R/W
OUTPUT_ENABLE
DATA_OUT
LOAD_ENABLE

RX_RAM
(n x 16)

LOAD_ENABLE
DATA_OUT
DATA_IN
ADDRESS
R/W
OUTPUT_ENABLE

MUX
MUX

T FF

RX_RAM_DATA
RX_RAM_WRITE_ADR
RX_RAM_READ_ADR
INFO_FIELD
LOAD_RAM_BYTE
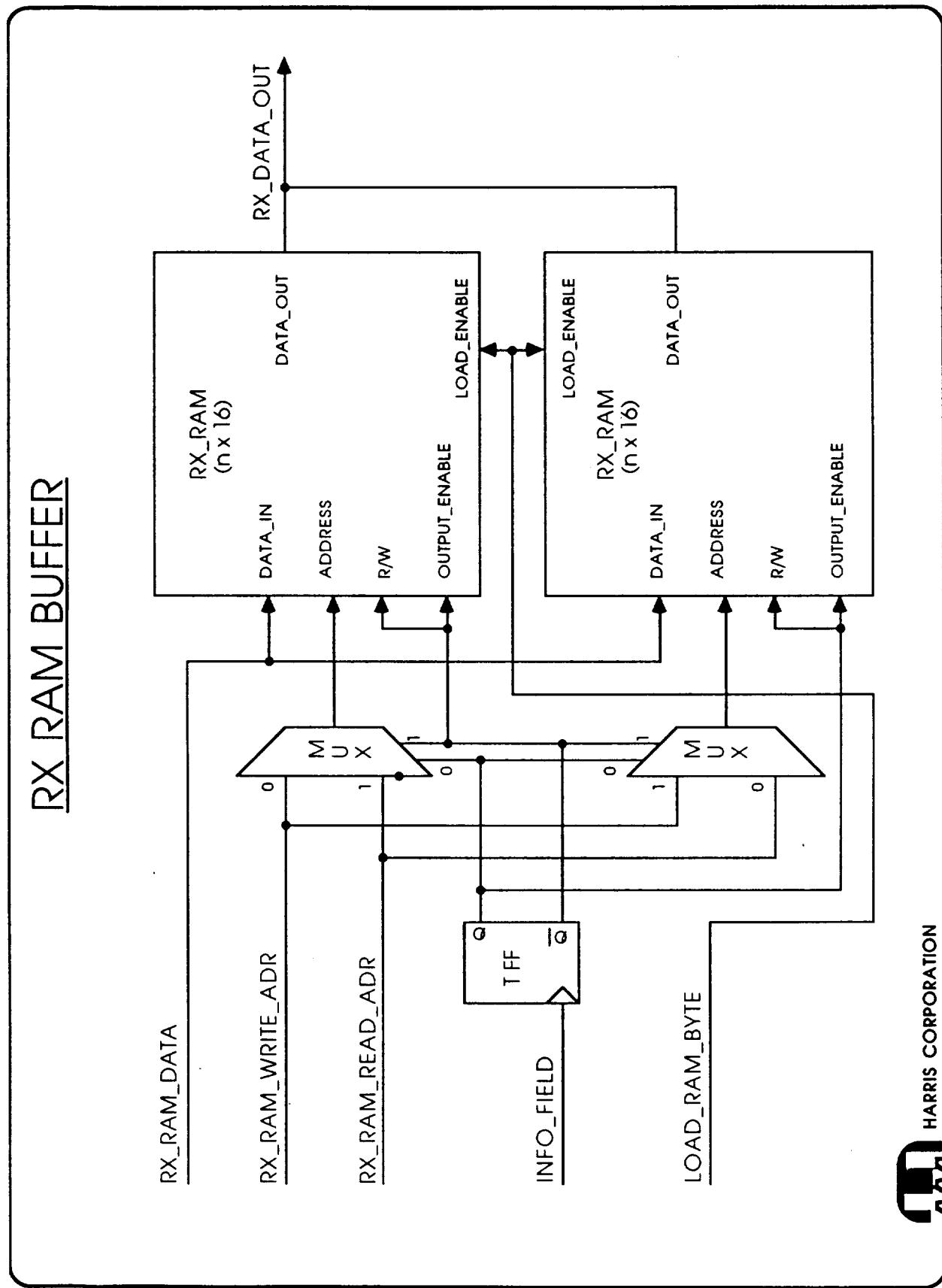
HARRIS CORPORATION
GOVERNMENT AEROSPACE SYSTEMS DIVISION

rx_ram_buffer

35

TRANSMIT CHAIN

The transmit chain of the terminal is illustrated in the following figures. The function and operation of each component is, for all practical purposes, the inverse of its counterpart in the receive chain.

Tx DMA CONTROLLER

Tx dma controller

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37

Tx RAM BUFFER

RX_DATA_OUT

RX_RAM (n x 16)
- DATA_IN
- ADDRESS
- R/W
- OUTPUT_ENABLE
- DATA_OUT
- LOAD_ENABLE

RX_RAM (n x 16)
- LOAD_ENABLE
- DATA_IN
- ADDRESS
- R/W
- OUTPUT_ENABLE
- DATA_OUT

MUX

MUX

T FF

TX_RAM_DATA

TX_RAM_WRITE_ADR

TX_RAM_READ_ADR

LOAD_HEADER

LOAD_RAM_BYTE

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Tx_ram_buffer

38
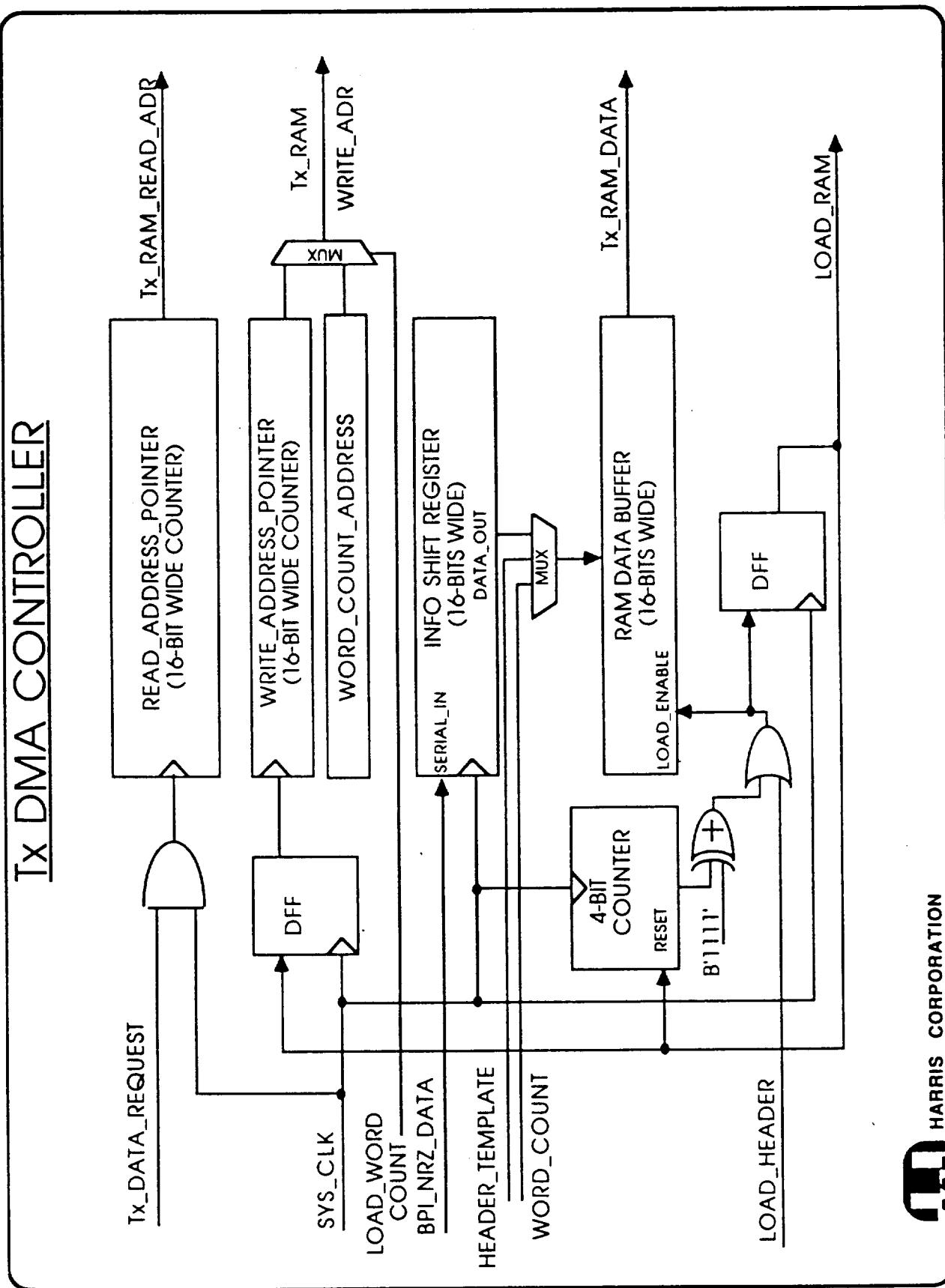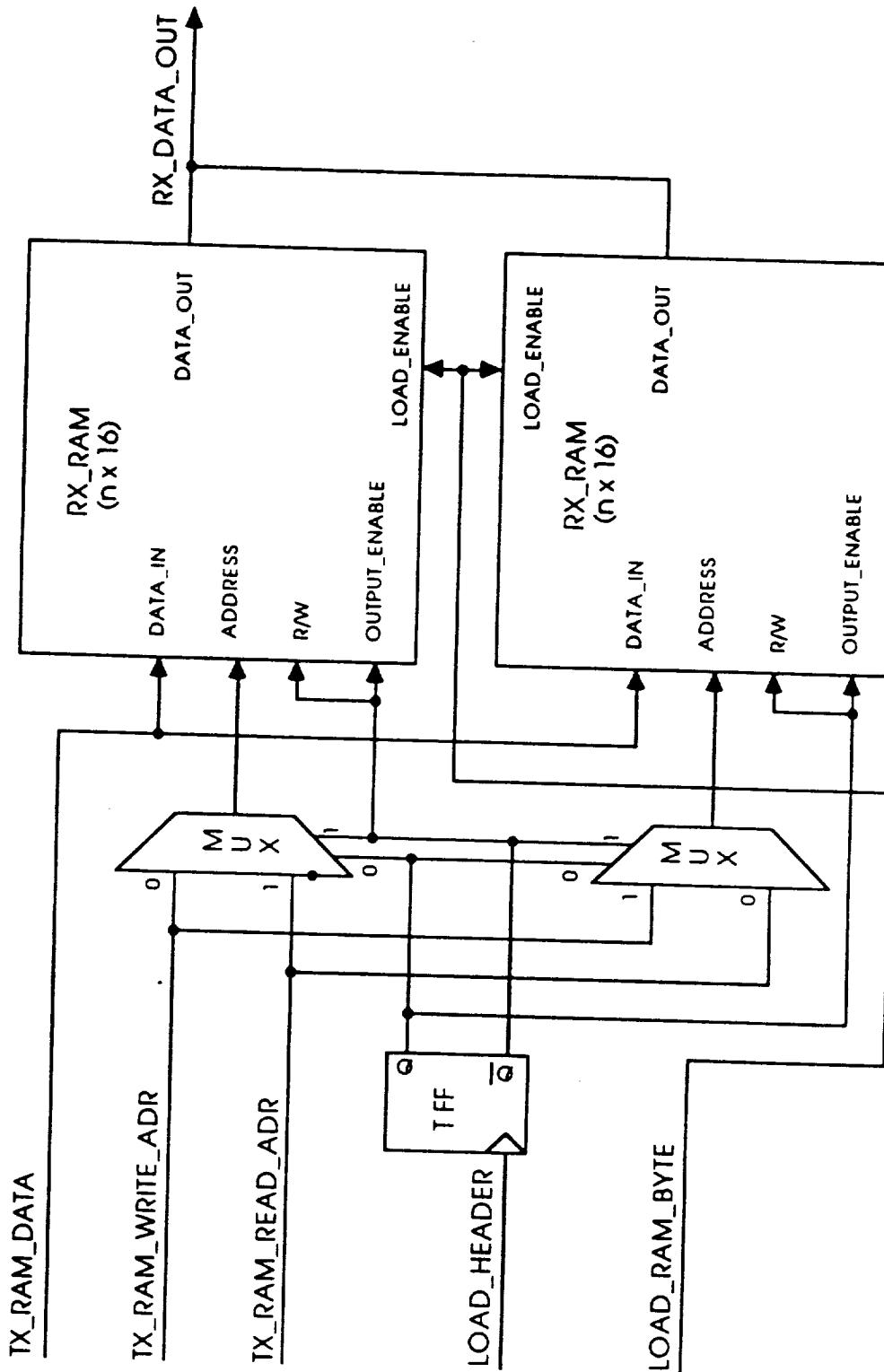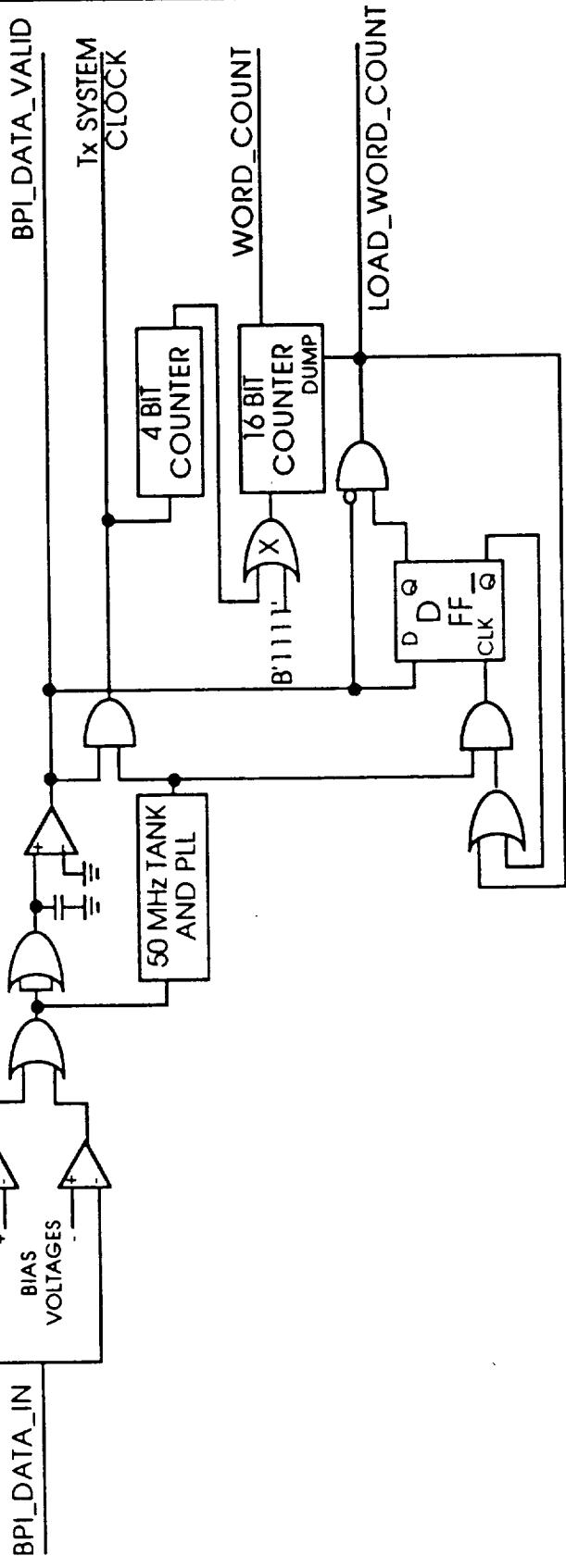
Tx DATA FORMATER

Tx ENCODER
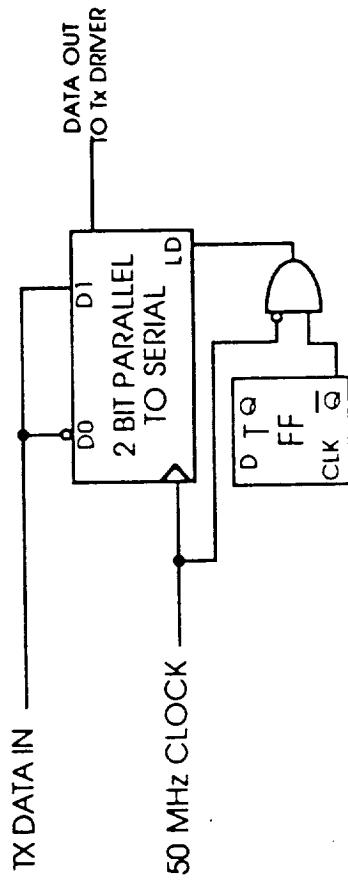
HARRIS CORPORATION
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Tx data formatter

39

RESOURCE UTILIZATION SUMMARY

Using the preceding receive and transmit components, the utilization chart was developed. Excluding the C&T local bus interface, the implementation requirements are quite modest. Therefore, it is recommended that the digital functions be put on a single chip, the optical sources and detectors be mounted into hybrids, and the entire electronics assembly be incorporated into the focal plan of the terminal. This will eliminate complex optical paths through the mechanical assemblies.

TRANSCEIVER RESOURCE UTILIZATION

SYSTEM COMPONENT	GATE COUNT	SPEED (MHz)	POWER (mW)
DATA RECEIVER	60	50	60
RX RAM BUFFER	96	1.5625	3
RX DMA CONTROLLER	571	25	285
RX DATA FORMATTER	696	50%@25 50%@1.5625	185
DATA ENCODER	36	5	36
TX RAM BUFFER	96	.03125	96
TX DMA CONTROLLER	908	5	5
TX DATA FORMATTER	350	5	35
BPI INTERFACE	CURRENTLY BEING DEFINED BY WP2		
C & T LOCAL BUS INTERFACE	SUPPLIED BY DATA MANAGEMENT SYSTEM		
MEMORY			1000
TOTAL	2811		1669

ALLOW 50% MARGIN (BIT, ETC.): POWER= 2.5 WATTS

PART 2

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EXECUTIVE SUMMARY: REPORT OUTLINE

1.0 Introduction

2.0 Optical link trades

3.0 Acquisition/track/communication analysis

4.0 Gimbal configuration & angular coverage

5.0 Optical terminal design

6.0 Prox-Ops system design

7.0 Conclusions & recommended follow-on efforts

8.0 References

9.0 List of acronyms

44

EXECUTIVE SUMMARY

The purpose of this effort, conducted under Harris contract 8041766, was to devise conceptual designs for optical systems that meet the initial and growth phase requirements for communication between Space Station Freedom (SSF) and a host of co-orbiting platforms. This proximity-operation (Prox-Ops) communication was planned for implementation using Ku-band microwave technology, where the presence of frequency allocation and interference problems could place unacceptable operational constraints on SSF. Since these problems do not exist in the optical spectral region, it offers the potential to provide significant benefit to the evolutionary space station.

The platforms considered in Prox-Ops were the Orbital Maneuvering Vehicle (OMV), National Space Transportation System (NSTS or space shuttle), Mobile Servicing Center (MSC), Flight Telerobotics Servicer (FTS), Extra Vehicular Activity/Manned Maneuvering Unit (EVA/MMU), and co-orbiting satellite platforms. Such a diverse set of platforms placed a large range of performance requirements upon the optical system design. Specifically, several of the platforms remain within a 1-km radius of SSF, and initial uncertainties in their position could result in large angular uncertainties that must be quickly narrowed during a mutual acquistion phase for compatibility with the typical optical beamwidths required to close the closed-loop tracking and communication links. For the long-range Prox-Ops platforms (37-km range in the initial phase, 2000-km in the growth phase), transmitter power requirements begin to impact the design, particularly since the system must operate in the presence of sizable (e.g., sunlit Earth and Moon) optical backgrounds.

The design philosophy for this effort was two-sided. First, available optical components were assumed throughout to minimize developmental risk. Second, every effort possible was made to minimize system size, weight, and prime power, by combining necessary subsystem functions (acquisition, tracking, and communication) using single active components (lasers and detectors) rather than the traditional approach that uses separate devices tailored to the specific subsystem needs. Resulting from this effort are designs that satisfy the Prox-Ops system requirements, but requiring follow-on development effort in certain key areas to establish the operational validity of the system.

EXECUTIVE SUMMARY (cont.)

As shown, this report is divided into nine sections, concentrating on design of the Prox-Ops acquisition, tracking, communication, and optomechanical subsystems. Following the mission description in the Introduction, tradeoffs involved in designing the above subsystems are outlined, and preliminary tradeoff conclusions are indicated. This is followed by an in-depth analysis of the Prox-Ops acquisition, tracking, and communication performance, resulting in selection of appropriate optoelectronic components that satisfy the mission. A key element in the acquisition analysis and design is a coarse acquisiton sensor that rapidly reduces a full-spherical field of uncertainty (FOU) to about a 1-degree FOU, allowing rapid reacquisition by the laser terminal.

Descriptions and engineering drawings of gimbal designs that provide the necessary angular coverage for Prox-Ops are then combined with the above analytical results to formulate the Prox-Ops optical terminal designs . A system-level design is then formulated that supports up to four simultaneous users within the Prox-Ops communication zone. Included in this section are baseline wavelength allocations, discussions on coping with line-of-sight obscurations, and system level drawings indicating the relative sizes of the optical terminals and SSF. The conclusions briefly summarize the design, identify the technological areas where advances could significantly impact the Prox-Ops system, and give recommendations for follow-on work necessary to transition the proposed design to operational status.

1.0   INTRODUCTION

This section provides a general description of the Prox-Ops mission, including the types of vehicles considered and the communication requirements between each vehicle and SSF (data rates and ranges). This is followed by discussions of the motivating factors for the study and the key issues that impact the design of an optical Prox-Ops. Solutions to these issues form the basis for the remainder of this report.

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1.0 INTRODUCTION

- Mission definition

- Communication zones

- Motivation for optical approach

- Key issues for optical Prox-Ops

TOP-LEVEL MISSION DEFINITION

The Prox-Ops mission is summarized. As shown, the vehicles considered in Prox-Ops are:

Co-orbiting Free Flyer

Extra Vehicular Activity with a Manned Maneuvering Unit (EVA/MMU)

Flight Telerobotics Servicer (FTS)

National Space Transportation System (STS or Space Shuttle)

Orbital Maneuvering Vehicle (OMV)

As described elsewhere   the Prox-Ops mission supports the transfer of audio, digitized video, telemetry/commands, text, graphics, and other data between SSF and the above cluster of vehicles. The main mission is to return digitized video from the various platforms to SSF. Inclusion of a small overhead data-handling capability brings the return links to the assumed 25-Mbps data rate. The 0.5-Mbps forward links deliver tracking, telemetry, and command (TT&C) data to each vehicle, heads-up display data to the EVA/MMU, and digitized voice to the STS. The EVA/MMU, FTS, and MSC remain within a 1-km range of SSF; the OMV, STS, and co-orbiting satellite platforms can extend out to ranges of 37 km (initial phase) or 2000 km (growth phase). Finally, the system must support up to four simultaneous users, thus requiring a multiple-access optical communication system with a full-spherical angular coverage.

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TOP-LEVEL MISSION DEFINITION

CO-ORBITERS

FTS

MSC

NSTS

EVA/MMU
(In pairs)

OMV
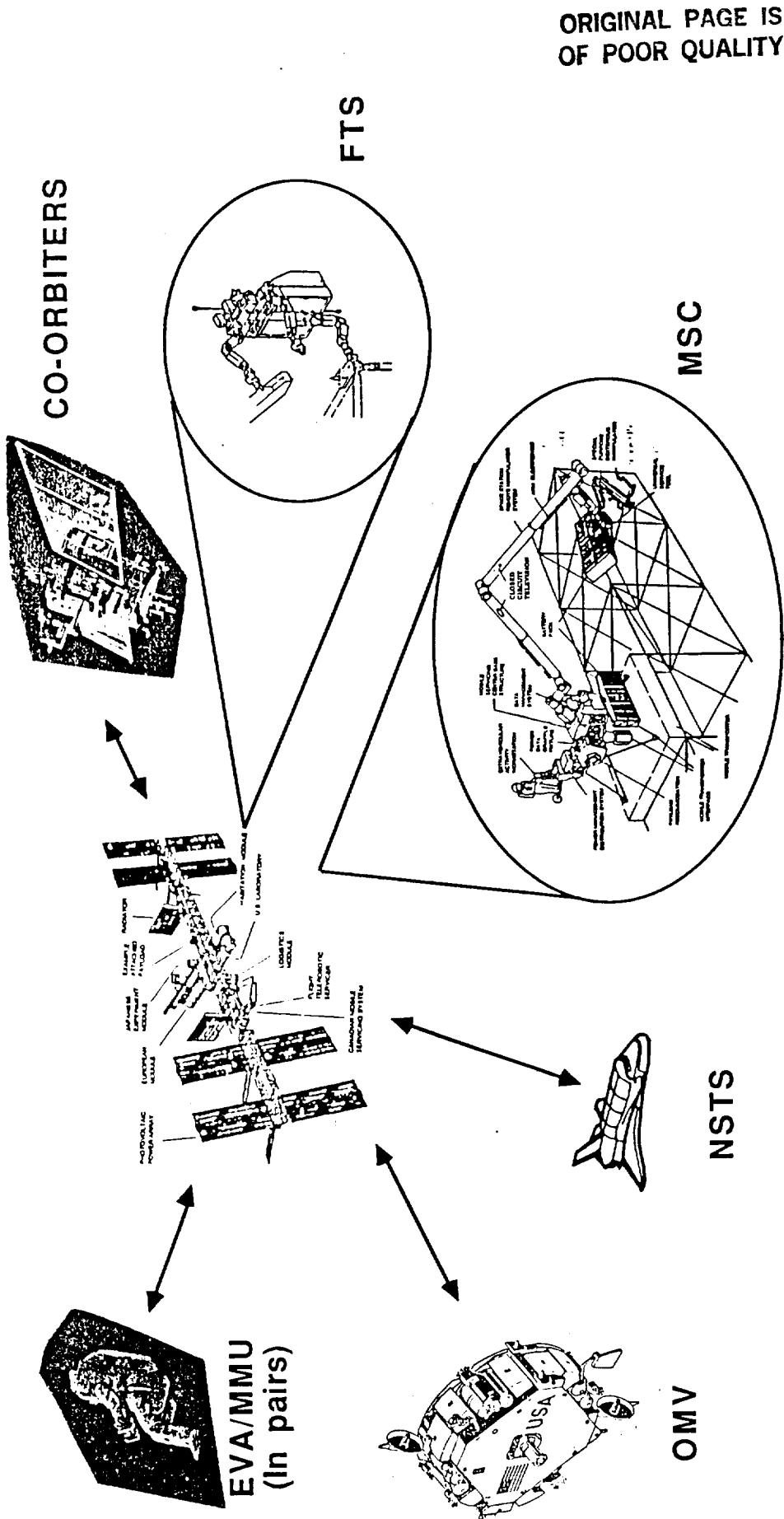
- Return data (vehicle to SSF) : 25-Mbps digitized video & overhead

- Forward data (SSF to vehicle): 500-kbps TT&C/lifeline

- Up to four simultaneous bidirectional links

49

MISSION DEFINITION DETAILS

The Prox-Ops communication zones   are shown, indicating the regions of command, control, and communication pertaining to SSF. As shown, the control zones form a curvilinear coordinate system with SSF at its center that rotates with SSF along its orbit. The control zones extend 9 km on either side of the SSF orbital plane. In the initial phase, SSF is responsible for communication with vehicles in the two nearest zones:

Proximity Zone - 1-km maximum range (EVA/MMU, MSC, FTS, Docking STS)
Command and Control Zone - 37-km maximum range (OMV, STS)

In the growth phase, the communication zone extends out to 2000 km to include links with vehicles in the rendezvous and departure zones (OMV, STS), as well as the leading and trailing co-orbiting zones.

50

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MISSION DEFINITION DETAILS:
SPACE STATION ZONES OF COMMUNICATION
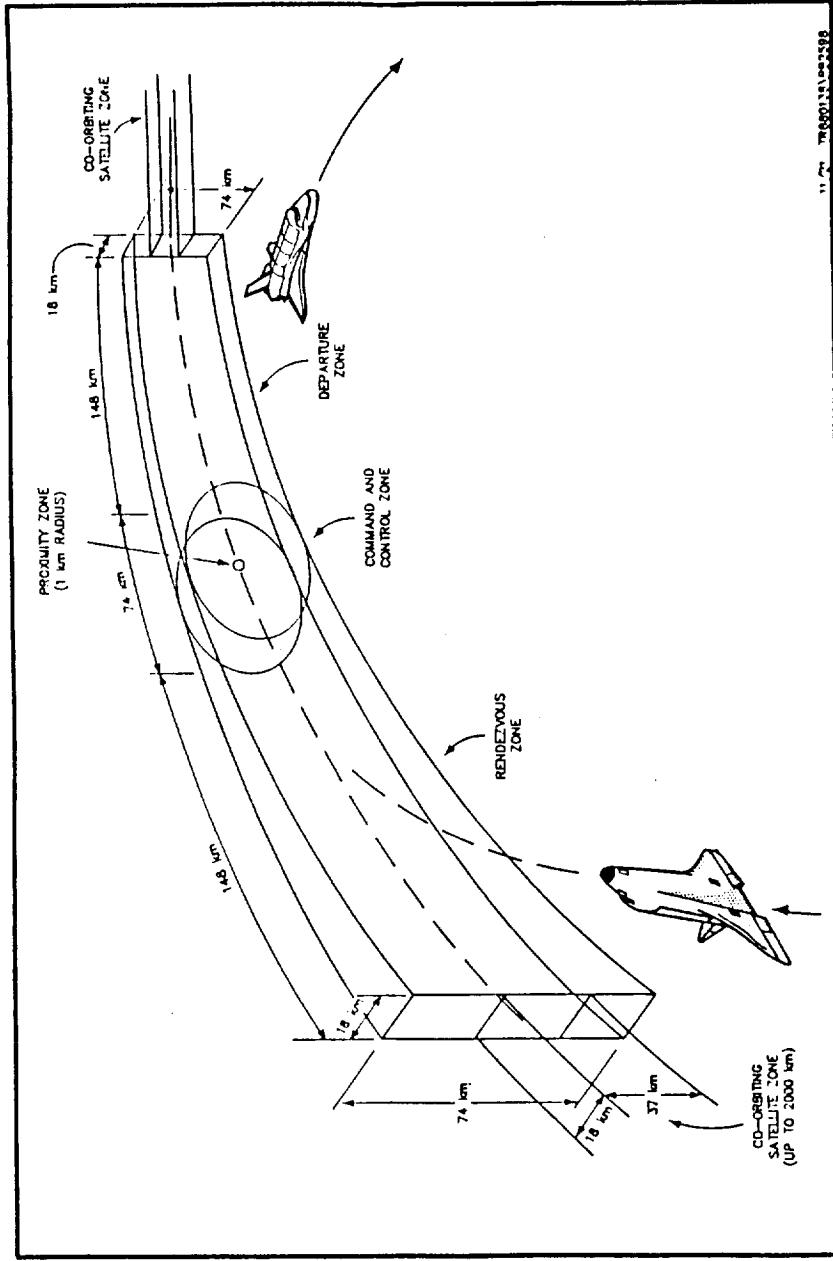
From P.W. Kwong and R.C. Bruno, "Lasercom Application to Space Station Freedom Cluster Communications Needs," Stanford Telecommunications, Inc., Reston, VA., Draft Final Report for NASA/Goddard Space Flight Center, Contract No. NAS5-30232, 20 December 1988.

MOTIVATION FOR OPTICAL APPROACH

The motivating factors behind this study effort are shown, and essentially rely on the widely known properties of optical systems: wide bandwidth capability, narrow transmit beams, small receive field of view (FOV), and unregulated, selectable carrier frequencies. These properties offer the potential for a multiple access system that is essentially interference-free and with the capability to accommodate system growth. An additional underlying feature of optical systems is their potential for satisfying the system requirements with a payload whose size, weight, and prime power (SWAP) impact is not severe.

Although it is beyond the scope of the present effort to complete a full system comparison between RF and optical carriers for this mission, several key tradeoff issues can be noted. First, an RF solution offers fairly broad transmit beams and wide receive FOVs that can be used in conjunction with well-established multiple-access schemes for implementation of a multiuser network. Two difficulties with such a system implementation are: (1) Techniques must be employed that reduce inter-user interference to acceptable levels, and this becomes increasingly difficult as the user count grows, and (2) The RF spectrum is rather crowded, so that carrier frequencies would be assigned to an RF Prox-Ops. In an optical Prox Ops, wavelengths can be selected and the well-known properties of optical beams can be used to provide essentially interference-free communications. Furthermore, the wide bandwidth capability of optical links can be exploited to accommodate system growth by using wavelength-division multiplexing and multiple receive terminals on SSF. However, the system benefits offered by an optical approach require solution to another set of system issues discussed on a later chart.

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FREQUENCY ALLOCATION AND INTERFERENCE ISSUES MOTIVATE OPTICAL APPROACH

- Large number of users implies need for interference-free communication

  - Optical systems typically use narrow beams and small receive FOVs

- Freedom to select optical carrier frequency (wavelength) aids in minimizing interference

  - RF carrier frequencies would be assigned to Prox-Ops
  - Potential interference with high-power, ground-based transmitters

- Large optical bandwidth accommodates system growth

  - WDM and multiple receive terminals on SSF

WIDE RANGE OF SYSTEM REQUIREMENTS IN PROX OPS

The Prox-Ops communication requirements can be sorted into the three distinct categories shown on this chart. For the first category, the major constraint is coping with possible LOS obscurations, best satisfied with multiple terminals., Otherwise, the system functions are readily achieved, owing to the extremely short range (200 m maximum) and well-known vehicle angular position. The second category represent the most challenging type for an optical Prox-Ops, since the typical positional uncertainties obtainable from the Global Positioning System (GPS), if available, result in very large relative angles. Two options can be pursued to achieve fast mutual acquisition (seconds) under such circumstances. Either acquisition receivers must be designed that scan or stare at very wide FOVs in the presence of sunlit-Earth backgrounds, or an operational scenario must be developed that reduces the FOU to acceptable levels before attempting mutual acquisition. Once acquisition is achieved, communication to the close-proximity vehicles demands an optical terminal with the largest possible angular coverage, thus shifting the burden to the coarse-pointing gimbal. Finally, since these vehicles can be very near SSF (particularly the EVA), LOS obscurations are a major concern, demanding a handover algorithm that copes with the prevalent, but predictable, obscurations.

The 37- and 2000-km zones are better suited to optical communication links, since they drive the design towards directed beams with accurate spatial tracking and narrow receive FOVs. In addition, due to the longer range, typical GPS positional uncertainties result in rather narrow relative angles; the acquisition FOU is instead driven by the vehicle boresight alignment uncertainty. A disadvantage in this category is that the designs tend to be transmitter-power limited, requiring a larger telescope diameter that increases payload mass. This effort is further hampered by the requirement to operate in the presence of large optical backgrounds.

54

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WIDE RANGE OF SYSTEM REQUIREMENTS IMPOSED BY THE VARIETY OF VEHICLES IN PROX-OPS

- Vehicles attached to SSF

  – FTS and MSC
  – Angular position well-known
  – Multiple terminals handle line-of-sight obscurations

- Close-proximity vehicles (up to 1-km range)

  – EVA/MMU, OMV, and docking Shuttle
  – Large angular coverage
  – Fast acquisition difficult with large FOU
  – Burden shifts to gimbal after acquisition
  – Line-of-sight obscurations are prevalent

- Long-range vehicles (up to 37 km for initial phase; 2000 km for growth phase)

  – OMV, Shuttle, and co-orbiters
  – Smaller FOU eases acquisition
  – Suited to directed beams with accurate spatial tracking
  – Optical background impacts required transmitter power, particularly in the growth phase

KEY ISSUES FOR OPTICAL PROX-OPS

Shown on this chart are several of the key system issues that must be addressed in designing an optical Prox-Ops. Solutions to the first four issues are required to provide short-range Prox-Ops communications; the last bullet is an obvious general requirement. With regard to link outages, the system is designed to cope with LOS obscurations while eliminating significant downtime (more detail later). However, under normal operating conditions, solar conjunction outage is considered acceptable. The details relating to the issues shown on this chart are the essence of this report.

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AN OPTICAL PROX-OPS MUST SOLVE SEVERAL KEY ISSUES

- Fast acquisition with a large FOU

- Spherical angular coverage with a lightweight transceiver

- Multiple access to a variety of vehicles

- No outages despite line-of-sight obscurations

- Small size, weight, and power; particularly on the vehicles

57

2.0 OPTICAL LINK TRADEOFFS

This chart outlines the tradeoff areas for design of an optical Prox-Ops. The key item unique to this study is in assessing whether or not the comparatively small ranges and data rates allow reductions in system complexity and SWAP by combining the acquisition (ACQ), tracking, and communication (COMM) functions with single active optoelectronic components. This design approach therefore assesses the "give and take" compromises associated with this assimilation process, and differs from that found in the many other optical communication studies to date, where the three subsystem functions are performed by components selected to meet their diverse needs.

The section begins with assessments of the various optical components, and progresses towards a system-level comparison of approaches to Prox-Ops. Qualitative conclusions from these tradeoffs serve as the basis for the in-depth quantitative analyses in Section 3.0 that show the validity of the selections.

58

2.0 OPTICAL COMMUNICATION LINK TRADEOFFS

- Source trades: LEDs vs lasers

- Detector trades

    - PINs vs APDs
    - LECs
    - CCDs and CIDs
    - Quad cells

- Combining acq, track, and communication functions

- Optical background sources

- Telescope trades: On-axis vs off-axis

- Pros and cons of various system approaches

- Qualitative tradeoff conclusions

SOURCE TRADEOFFS

This chart summarizes the tradeoffs relating to optical sources for Prox-Ops. Several optical sources have been considered in the past for implementing free-space optical communication links, including the carbon dioxide gas laser, the Nd:YAG solid-state laser, and the GaAlAs semiconductor diode laser. These studies have shown that the GaAlAs diode laser possesses several unique properties that make it a very attractive choice for this application, including small size, high electrical-to-optical conversion efficiency, direct modulation capability, wavelength selectability over a wide interval, and the reliability features inherent in a semiconductor device. An additional feature favoring GaAlAs technology is the widespread interest it receives in other application areas (optical disks and bar-code readers), which suggests that the future should bring rapid advances in the state of the art. Further, the relatively short-range and low-data-rate requirements in Prox-Ops, suggest that the typical optical power limitations from diode laser sources should not be severe in Prox-Ops. The analysis in this report avoids problems with regard to diode reliability by baselining devices with 50-mW average power.

A secondary source trade is between GaAlAs diode lasers and light emitting diodes (LEDs), but this is quickly put to rest. The laser, being a coherent device, is preferred for the high optical background conditions of Prox Ops, because of its narrower linewidth that allows more-efficient background rejection at the receiver.

SOURCE TRADEOFFS

- GaAlAs sources selected to minimize risk and payload impact

- Diode laser coherence properties are favored for free-space systems

  - Narrower linewidth allows more-efficient background rejection than with LEDs

- 50-mW diodes baselined to ensure high reliability

DETECTOR TRADEOFFS

This chart outlines the detector subsystem trades described on the next several charts. The first trade is between various optical detection methods; the two major contenders being direct and heterodyne detection. Direct detection is selected for Prox-Ops since it reduces complexity by placing fewer operational constraints on the system. Heterodyne systems offer better sensitivity, but this can be sacrificed for this mission. The background-rejection characteristics of the heterodyne approach would be attractive in Prox-Ops, but the advantage gained is not worth the increased complexity, particularly at short ranges where sufficient transmitter power is available to combat the background shot noise.

The detector tradeoff has added significance in Prox-Ops because of the lower range and data rate compared to those in typical optical communication systems. As a result, a major point of investigation is whether a single detector can be used for ACQ, track, and COMM, or are separate detectors required for each subsystem. The first design approach allows a reduction in payload complexity and SWAP, whereas the second approach allows each subsystem design to be tailored to specific and diverse needs. Before addressing this issue, however, candidate detectors for each of the three subsystems are compared.

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DETECTOR TRADEOFFS

- Direct-detection receivers assumed throughout to minimize risk and complexity

- Acquisition detector trades

- Tracking detector trades

- Communication detector trades

- Separate acquisition, tracking, and communication detectors vs single detector approach

ACQUISITION DETECTOR TRADES

Shown on this chart are the key characteristics of those detectors normally considered for optical acquisition, which typically demands wide FOV, efficient background discrimination, and high resolution.

The lateral effects cell (LEC) is the simplest and least expensive of the three, but suffers from inferior performance. This device, being simply a piece of silicon with four leads situated in the top-center, right-center, bottom-center, and left-center portions of the chip, is typically large (several centimeters square) for wide-FOV coverage. This implies a large detector capacitance and low bandwidth (less than 10's of kHz typical) that are not suited to communication. Another problem with LECs is the low sensitivity and low resolution resulting from their operation that senses focal spot position by comparing photogenerated carriers that have migrated to each of the four leads.

The quadrant detectors offer much-improved sensitivity and resolution over the LEC and are not complicated to implement, particularly in the PIN configuration. Their suitability for ACQ becomes an assessment of their coverage FOV, and this could be key for the short-range Prox-Ops links.

The array detector is the normal choice for laser acquisiton for the reasons indicated. Array detectors (particularly CCDs) typically suffer from low (10-100 Hz) bandwidth capability, but are sufficient for most ACQ detector update rates. The CID subarray approach can support larger bandwidths, but the performance suffers from sizable readout noise.

The PIN quad cell has been baselined for Prox-Ops acquisition, mainly because of the potential for providing the ACQ, track, and COMM functions. Further assessements in this report indicate the limitations associated with this baseline selection.

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ACQUISITION DETECTOR TRADES

- Lateral effects cell

  - Inexpensive, Simple implementation
  - Low sensitivity, Low resolution
  - Wide FOV achievable, but with low bandwidth (large detector capacitance), could limit background discrimination

- Quadrant detector (PIN or avalanche)

  - Low complexity, Limited FOV, Medium resolution, High sensitivity
  - High bandwidth; supports acquisition, fine tracking, and low-data-rate communication
  - Modulated beacon approach discriminates against large backgrounds

- CCD/CID array detector

  - More complex and more expensive than LEC or quadrant detector
  - Large number of pixels provides wide FOV; small pixel FOV provides background discrimination and high resolution
  - CCD provides low bandwidth; CID subarray could potentially support fine tracking and 500-kbps communication (development items)
  - Receive optical power limited by pixel saturation ($\approx 1.4/\tau$ pW; τ = integration time)
  - Readout noise can limit sensitivity (CID worse than CCD)

- PIN Quadrant detector recommended for Prox-Ops, unless ACQ FOU drives towards CCD/CID

TRACK DETECTOR TRADES

The detector trades for fine tracking essentially involve a comparison of quad cells and charge transfer arrays, with key issues being tracking bandwidth and detector sensitivity. Tracking bandwidth requirements are driven by desired platform-disturbance-rejection characteristics [1], and detector sensitivity must consider the effects of the large optical backgrounds in Prox-Ops. Efficient disturbance rejection demands tracking bandwidths on order 5 kHz, thus favoring the quad cell. Since sensitivity can be sacrificed in Prox-Ops, the PIN detector is the leading candidate. Furthermore, under large background conditions, the optimum avalanche gain is driven towards smaller values   thus reducing the sensitivity improvement over PIN devices. The key question to be answered by the analysis to follow is whether the desired tracking performance can be achieved despite the large detector FOV required to support mutual acquisition.

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TRACK DETECTOR TRADES

- Quadrant detector (PIN or avalanche)

  - Well established for fine-tracking application
  - High bandwidth; supports fine tracking and low-data-rate communication
  - Avalanche device offers higher sensitivity, but requires large bias voltage
  - Modulated beacon approach discriminates against large backgrounds, but entails separate track and communication detectors

- CCD/CID array detector

  - More complex than quadrant detector
  - CCD array size limited by readout frequency
  - CID subarray can be read out at kHz rates, but its suitability for fine tracking and low-data-rate communication is a development item
  - Small pixel FOV allows high tracking accuracy in presence of large optical backgrounds
  - Readout noise can limit sensitivity (CID worse than CCD)

- PIN Quadrant detector recommended for Prox-Ops

COMMUNICATION DETECTOR TRADES

The trade space for communications detectors is driven by the bandwidth and sensitivity requirements. In most optical communication systems, bandwidth is rather large (near a GHz) and silicon photodiodes are preferred. Since such optical links are typically power-limited, avalanche photodiodes (APDs) are usually selected to improve receiver sensitivity. Prox-Ops is unique in that both bandwidth and range are smaller than typical, allowing consideration of the quad cell and array detectors for communication. Bandwidth limitations preclude use of an array detector in the 25-Mbps SSF terminals. Their use in the 0.5-Mbps vehicle receivers, although theoretically possible, is somewhat risky to propose and would require a capability demonstration.

The quadrant detector 3-dB bandwidths shown on the chart are based on the following commercial devices:

PIN quadrant detector - United Detector Technologies (UDT) Model SPOT/4D (16-pF capacitance)
Avalanche quadrant detector - RCA Model C30927E (3-pF capacitance)

68

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COMMUNICATION DETECTOR TRADES

- Silicon photodiode (PIN or avalanche)

  - Multi-GHz bandwidth
  - Avalanche device offers higher sensitivity, but requires large bias voltage

- Quadrant detector (PIN or avalanche)

  - Bandwidth supports Prox-Ops requirements
    -- Demodulated PIN quad cell "total" output provides 35-MHz communication bandwidth
    -- Avalanche quad cell provides 100-MHz communication bandwidth
  - Lower sensitivity than photodiode

- CID array detector

  - 500-kbps communication appears feasible, but difficult, with a CID subarray
  - Lower sensitivity than photodiode or quad cell

- Conclusion: Baseline PIN quadrant detector for Prox Ops

69

SINGLE DETECTOR APPROACH FOR PROX-OPS

Due to the low data rate and short ranges in Prox-Ops, it is possible to consider using one detector to perform ACQ, track, and COMM. This differs from the traditional design approach which baselines a CCD array detector for low-update-rate (10-100 Hz), wide-FOV (5 mrad) ACQ, a quadrant detector for medium-FOV (150 μrad), moderate update rate (5 kHz) track, and an avalanche photodiode for narrow-FOV (25 μrad), high-data-rate (GHz) communication. Previous charts have indicated the PIN quadrant detector as the baseline choice for Prox-Ops ACQ, track, and COMM, with the strain being placed on its ability to provide fast ACQ despite the optical backgrounds in large FOVs. The small quadrant detector will be shown to have limited FOV, but an operational scenario will be developed that allows it to support Prox-Ops acquisition. Finally, the PIN quad device is selected over the avalanche quad cell to reduce complexity and because the improved sensitivity of the latter can be sacrificed in this mission. Also, as discussed earlier, when operating with large receive backgrounds, the optimum avalanche gain is driven towards unity, thus approaching the PIN detector performance.

70

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PROX-OPS REQUIREMENTS CAN CONCEIVABLY BE MET BY A SINGLE DETECTOR

- Many laser communication systems baseline

  - CCD array for wide-FOV, low-update-rate ACQ
  - Avalanche quad cell for medium-FOV, moderate-update-rate track
  - Avalanche photodiode for narrow-FOV, high-data-rate communication

- ACQ, TRK, and COMM subsystems can then be tailored to meet their diverse requirements, but system SWAP and complexity are increased

- Prox-Ops data rate and range are both comparatively small

  - A quad cell can conceivably satisfy the ACQ, TRK, and COMM requirements
  - PIN device preferred, since avalanche sensitivity can be sacrificed for short range and low data rate
  - Quad-cell FOV must be kept under control to allow fast ACQ despite typical optical backgrounds
  - FOV also constrained by detector size and the optical design (f/# > 1)

OPTICAL BACKGROUND SOURCES

The table shows the characteristics of the major optical background sources in Prox-Ops, and indicates which pertain to the various links. Since solar outage is acceptable, the key background drivers are the sunlit Earth for the short-range links (up to 9 km), and, for the longer range links (up to 2000 km), the Moon for quadrant-detector systems and Venus for charge-transfer-array systems, respectively.

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MAJOR OPTICAL BACKGROUND SOURCES

SOURCE	SIZE AT 150-NAUT. MILE ORBIT	FULL IRRADIANCE (W/m²A)	SHORT-RANGE LINKS	LONG-RANGE LINKS @ R = 9 km	37 km	2000 km
Sun	9.3 mrad	0.105	✓	✓	✓	✓
Earth	1.53 rad	0.053	✓	✓		
Stars	< 1 μrad	$2 \times 10^{-(11 + 0.4m)}$ (magnitude = m)	✓	✓	✓	✓
Venus	85 μ rad	1.0×10^{-10}	✓	✓	✓	✓
Moon	9042 μrad	2.7×10^{-7}	✓	✓	✓	✓

73

DETECTOR FOV CONSTRAINTS

Since the short-range Prox-Ops links could have rather large initial FOUs, a large ACQ detector FOV is needed to eliminate receiver scanning during mutual acquisition. For example, positional uncertainties from GPS of ± 10 m correspond to a 400-mrad relative angle at 50-m range. For the sake of this assessment, consider a 500-mrad relative angle, and consider the impact of such a large FOU on the optical design. The first obvious constraint is that a large background power will be received in the large FOV. However, the short ranges in Prox-Ops will often allow this to be overcome by boosting the receive signal power to achieve an adequate signal-to-noise ratio (SNR) despite the large background shot noise.

A secondary item for concern when designing an optical system for such large FOVs is the f/#. Reference [2] gives a good description of the issues involved, and these are summarized on this and the following chart. The discussion there shows that good imagery is difficult to achieve unless the f/# is greater than unity. As an example of the ramifications of this, consider the example shown, where it is desired to achieve a 500-mrad FOV with a typical 2-mm quadrant detector. As shown, the optical design constrains the focal length to less than 4 mm, which implies an aperture smaller than 4 mm. Such a small aperture reduces the signal photon count, making it difficult to close the communication link without requiring a high-power transmitter on the other end of the link.

DETECTOR FOV CONSTRAINTS

- Large initial FOU implies large ACQ detector FOV to minimize or eliminate receiver scanning

- Receive optical background increases as the square of the FOV

- Detector FOV also constrained by the optical design

  - f/# > 1 design is most desirable

- Consider the following example:
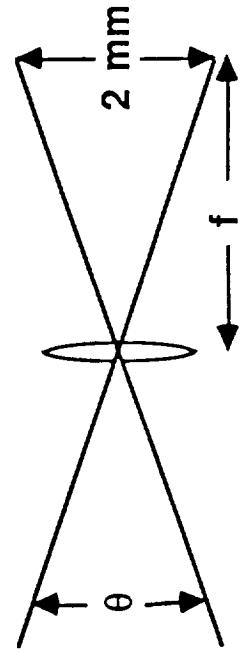
A 2-mm quadrant detector requires $\theta \cdot f \le 2$ mm

For a 0.5-radian field, $f \le 4$ mm. But a large aperture D is needed to collect a large number of signal photons.

DETECTOR FOV CONSTRAINTS (cont.)

This chart lists the consequences of the example outlined on the previous chart, and shows that fast optics entail a sophisticated design that is expected to be rather lossy. Although possible to use a brute-force optical design that supports such wide FOVs, this is not a trivial task and has several shortcomings. The preferred design approach reduces the FOU to the lowest possible value, by devising an operational scenario that takes advantage of the Prox-Ops system boundary conditions.

DETECTOR FOV CONSTRAINTS (cont.)

If D = 10 mm and f = 4 mm, the lens is f/0.4. This implies a 102-degree cone, and the following must be carefully considered:

(1) Depth of field - For 100-micron spot size no aberration, and no field curvature it is ΔZ = 80 microns

(2) Field curvature - Since this varies as $(D/f)^2$ and is ~ 5 microns for a good f/1.8 camera lens, it is 100 microns here. This gives a spot size of approximately 250 microns.

(3) f/0.4 will require about five air-spaced elements if each has a 15-deg incidence angle on both sides (i.e., to provide reasonable image quality). This entails an extensive design with critical alignments, etc., and system will be lossy due to vignetting.

77
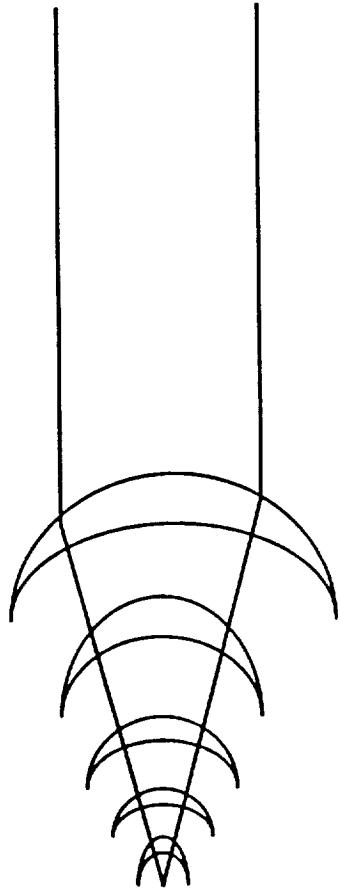
QUALITATIVE TRADEOFF CONCLUSIONS

This chart summarizes the component-level baseline selections discussed on previous charts. The FOV limitations are based on aperture sizes baselined for the SSF (10-cm), long-range-vehicle (10-cm), and short-range-vehicle (1-cm) terminals. Section 3.0 uses these baseline selections to assess the ACQ, track, and COMM link performances. Additional components are included in the analysis to compare the performances of the alternatives described on previous charts.

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QUALITATIVE TRADEOFF CONCLUSIONS

- GaAlAs diode laser transmitter (50-mW average power)

- Direct-detection receivers

- PIN quad cell for ACQ, TRK, and COMM

- f/# > 1 implies

  - FOV < 25 mrad for 2.5-mm PIN quad cell, 10-cm aperture
  - FOV < 250 mrad for 2.5-mm PIN quad cell, 1-cm aperture

- In-depth quantitative analysis solidifies the design (Section 3.0)

TELESCOPE TRADES

This chart summarizes the telescope design trades. In Prox-Ops, complexity and weight are both reduced by selecting off-axis telescopes with Coude' optical paths. As discussed in Section 4.0, a gimballed terminal was considered for the 1-cm system, but this alternative increased payload weight.

TELESCOPE CONCEPT TRADEOFF

- Telescope options include

  - Dual transmit and receive telescopes
  - Single telescope with an optical isolation technique

- Single telescope options include

  - On-axis with obscuration
  - On-axis without obscuration (refractive)
  - Off-axis without obscuration

- Baseline selections provide low complexity and light weight

  - On-axis with obscuration for SSF and
    long-range vehicles (OMV, Shuttle, co-orbiters)
  - On-axis refractive for short-range vehicles
    (EVA/MMU, FTS, MSC)
  - 10-cm aperture for SSF and long-range vehicles,
    1-cm aperture for short-range vehicles

OPTICAL DESIGN APPROACHES

The next several charts list system-level approaches considered for Prox-Ops, and highlight their key advantages and disadvantages.

The first approach has been assumed for the component-level discussions thus far. It offers a simple design with the potential for small payload impact, a particularly important concern on the vehicles. Its disadvantage is that achievement of fast acquisition with large initial FOU requires the most difficult acquisition procedure that scans both a beacon on SSF and the receiver FOV on the vehicle. Adoption of this system-level design approach therefore requires that an operational scenario be developed to control the acquisition FOU.

The second approach provides a wide FOV for acquisition, but tends toward a design that uses separate ACQ and track/COMM detectors; this increases payload complexity and weight. The multiple-target tracking feature would be useful on SSF, but requires that the targets remain within a limited FOV. This is an unacceptable constraint in Prox-Ops, since the cluster of vehicles can be anywhere within a sphere around SSF. In addition, the wide-FOV acquisition requirement will be shown unnecessary based on an operational scenario developed for normal operation. Finally, good imagery is difficult to achieve with the fisheye lens, and this reduces system efficiency.

82

PROX-OPS OPTICAL COMMUNICATION DESIGN APPROACHES

DESIGN APPROACH

Single-mode GaAlAs laser, single Si quadrant detector

Charge-transfer array detector (CCD or CID) and wide-FOV (fisheye) lens

SYSTEM IMPACT

Simple design - low complexity and potentially low size, weight, and prime power impact

One laser for acquisition, tracking, and communication

One detector for acquisition, tracking, and communication

Cannot support large acquisition FOU without simultaneous transmitter and receiver scanning

Multiple target tracking capability

Separate detectors for acquisition and track/communication (conceivable to receive 500-kbps data w/ CID subarray, but development required)

Fisheye lens typically f/2 or greater; difficult to focus on small detector w/ good image quality (substantial distortion)

Optical background collected by wide FOV could saturate CCD detector

OPTICAL DESIGN APPROACHES (cont.)

Both these approaches take advantage of the increased power available from semiconductor sources that cannot provide near-diffraction-limited beam quality. Beam quality can be sacrificed in Prox-Ops due to the low data rate and short range, but the increased optical power may not be necessary for the same reasons. Array sources are useful for reducing beacon scanning requirements during large-FOU ACQ, but performance is sacrificed for fine-track and communication, where efficient use of transmitter power prefers narrow optical beams with accurate spatial tracking. Furthermore, the large drive current and drive power of the array source result in a larger payload impact than for a 50-mW single-mode device. Array sources also have broader linewidths than single-mode devices, but this should not be a limiting factor with a typical 25-A bandpass filter. The two approaches on the chart differ only in the technique used to shape the oblong beam typically emitted by the array source: fiber-optic coupling versus a cylindrical focusing lens. In both cases, uniformity of the far-field intensity pattern is a concern.

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PROX-OPS OPTICAL COMMUNICATION
DESIGN APPROACHES (cont.)

DESIGN APPROACH

Incoherent GaAlAs diode laser array w/ fiber pigtail, PIN quadrant detector

Incoherent GaAlAs diode laser array w/ cylindrical lens, PIN quadrant detector

SYSTEM IMPACT

35-degree tophat beam is a good match to large FOU (up to 500 mrad)

Staring acquisition beacon and scanning acquisition receiver

Far-field speckle impacts performance

Large drive power and drive current for source

10 degree x 40 degree beam can be shaped to match large FOU

More efficient use of source power than fiber-coupled array (no fiber coupling loss)

Staring acquisition beacon and scanning acquisition receiver

"Rabbit-ear" far-field pattern typical

Large drive power and drive current for source

OPTICAL DESIGN APPROACHES (cont.)

The first two approaches on this chart attempt to alleviate or eliminate transmitter pointing requirements. This is an interesting consideration for Prox-Ops due to the need for full spherical angular coverage; a gimbal that provides such coverage is expected to be a system weight driver. The first approach considers duplication of laser transmitters on SSF to provide a hemispherical coverage. The utility of this approach is questionable on two grounds. First, since Prox-Ops is a bidirectional communication system, a receiver pointing requirement remains over the full hemisphere. Furthermore, as shown in Section 3.0, the beamwidths required to close the tracking and communication links requires many lasers (thousands) to be used to provide a full hemispherical coverage. The complexity and weight associated with such a large source count makes this approach quite unattractive.

The second approach follows along the same lines, and provide a very large total transmitter power. However, its complexity and the sheer number of devices needed to provide such a demanding angular coverage detracts from its usefulness.

The final approach is the only one not considering the GaAlAs laser technology. The impetus for this option is two-fold: (1) A larger output power is readily achieved with the Nd:YAG transmitter, and (2) The larger payload impact can be tolerated on SSF. The concerns with this approach are: (1) The limited transmit-wavelength selectability impacts the ability to support up to four simultaneous links with little or no inter-user interference, (2) An external modulator is needed to support the COMM requirements, (3) Detection of the 1.06-μm fundamental wavelength is typically inefficient (low quantum efficiency), and (4) Eye safety becomes an issue at the more-efficiently detected 0.532-μm doubled wavelength.

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PROX-OPS OPTICAL COMMUNICATION DESIGN APPROACHES (cont.)

DESIGN APPROACH

SYSTEM IMPACT

Hemispherical optical source,
PIN quadrant detector

No transmitter pointing requirement
Receiver pointing requirement remains
Numerous lasers req'd to comm over hemisphere
Large drive power and drive current for source
Inefficient use of laser power

Incoherent fiber bundle,
PIN quadrant detector

Optical output can match large initial FOU
Fiber length and optical alignment requirements
Potential for very high transmitter power
Large drive power and drive current for source

Nd:YAG laser on Space Station

Large size, weight, and prime power
   compared to diode laser source
External modulator for 500-kbps data link
Limited wavelength selectability for multiple links
Inefficient detectors at 1064 nm
Eye safety concerns at 532 nm

SOURCE BRIGHTNESS COMPARISON

This chart provides quantitative data to support the qualitative assessments provided on the three previous charts, and indicates the efficiency achieved when accurately pointing a narrow optical beam. Comparing the two extremes, the near-diffraction-limited source puts about 75-dB higher power on the detector than the hemispherical source that transmits 200 times the total laser power; a net link gain of nearly 100 dB.

The following system losses were assumed for the 1-km, SSF-to-vehicle links:

(1) Single-mode laser L = 12.5 dB
(2) Laser array L = 12.5 dB
(3) Hemispherical beam L = 10 dB
(4) Fiber bundle L = 10 dB

The above loss factors represent the sum of transmit-terminal obscuration loss (2.5 dB), transmit-terminal optical absorption loss (3 dB), receive-terminal optical absorption loss (3 dB), and link margin (4 dB). The last two cases assume a transmit telescope is not needed, thus eliminating the transmit obscuration loss.

FAR-FIELD BRIGHTNESS OF LASER SOURCES

Received signal power at distance Z from a source emitting P_O into divergence angle θ_T is

$$P_S = P_O \left\{ d / \theta_T Z \right\}^2 \ (10^{-L/10})$$

where d = receive aperture diameter = 1 cm (assumed for vehicle)
L = additional system losses

SSF SOURCE TYPE	P_O (mW)	θ_T	P_S @ 1-km range
Single-mode GaAlAs diode (1.25 x diff. lim.)	50	25.3 μrad (0.0015 deg)	0.4 mW
Incoherent GaAlAs diode laser array	500	0.6 rad (35 deg)	8 pW
Hemispherical beam	10 W	3.14 rad (180 deg)	10 pW
Incoherent fiber bundle (NA = 0.25, 40 fibers @ 25 mW ea.)	1000	0.52 rad (30 deg)	37 pW

89

RECOMMENDED DESIGN APPROACH

The system-level baseline selections are summarized, and based on the qualitative and quantitative assessments provided on previous charts. The baseline selections strive to achieve the goals outlined at the outset of minimizing complexity and SWAP impact, particularly on the vehicles. Achievement of these objectives places the design burden into the three areas indicated at the bottom of the chart. The next two sections discuss proposed solutions to these system issues. The difficult problems are clearly acquisition and angular coverage.

RECOMMENDED DESIGN APPROACH

- Single-mode GaAlAs diode laser transmitter

- Single Si quadrant detector

to

- Minimize complexity

- Control SWAP

implies need for

- Lightweight gimbal with hemispherical coverage

- Operational scenario to control FOU in normal operating mode

- Coarse acquisition sensor to accommodate large FOU in "dire straits" mode, particularly for EVA/MMU

3.0 ACQ/TRACK/COMM ANALYSES

This section provides in-depth analyses of the acquisition, tracking, and communication subsystems for the long- and short-range Prox-Ops links. These assessments serve to solidify the qualitative component- and system-level tradeoff conclusions discussed in the previous section.

The discussion begins with development of an operational scenario that controls a major design driver, the acquisition FOU. Based on mission boundary conditions, the FOU is baselined at 10 mrad for SSF, at 20-mrad for the long-range vehicles, and, under normal operating conditions, at essentially zero for the short-range vehicles. However, a worst-case scenario is also considered for the short-range vehicles whereby a full-spherical FOU must be rapidly reduced to about 1 degree. Handoff of the reduced FOU information to the optical terminal ACQ subsystem allows rapid reacquisition under such worst-case conditions.

The analysis begins by individually assessing the performance of the three optical subsystems, including such items as acquisition options, ACQ time, fine-tracking beamwidth, and COMM beamwidth. A coarse acquisition sensor design is then presented to accommodate the worst-case reacquisition condition, including qualitative and quantitative performance assessments. The above results are then summarized and combined to give baseline results for the ACQ, track, and COMM subsystems in the initial and growth phases.

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3.0 ACQ/TRACK/COMM ANALYSES

- Operational scenario

- Acquisition sequence options

- ACQ/Track/COMM link budget analyses

- Coarse acquisition sensor for EVA/MMU

- Summary

OPERATIONAL SCENARIO

The operational scenario described on this chart serves to control the ACQ FOU and allow achievement of fast ACQ in Prox-Ops. Beginning with the long-range vehicles (OMV, STS, co-orbiters) approaching SSF, acquisition is completed at long range, where the positional accuracies from the GPS correspond to small relative angles. Once acquired, the vehicles are tracked until they exit the Prox-Ops zone. Referring to a previous chart, the 9-km range represents the edge of the Prox-Ops zone parallel to Earth, i.e., for vehicles approaching SSF at its 150-nautical mile altitude. The 37-km range corresponds to entry into the Prox-Ops zone from above or below SSF, and the 2000-km range corresponds to entry along the co-orbiting satellite zone.

For vehicles docked at SSF, acquisition is achieved just before they leave, thus reducing the FOU to essentially zero. Difficult acquisition is never required by tracking the vehicles to the edge of the Prox-Ops zone.

For the FTS and MSC, initial angular positions are well-known and the range is short enough that SSF can readily illuminate them with a detectable beacon. SSF terminals are placed at each end of the MSC track, with a third terminal possibly in the middle. Should further assessments indicate a significantly large FTS/MSC FOU, the worst-case acquisition sensor briefly described below can be integrated into their optical terminals without imparting a significant payload impact.

The EVA/MMU links are acquired just after exiting SSF, using a "stop, look, listen" approach that essentially reduces the FOU to zero. They are then tracked out from and back to SSF. If the EVA/MMU weight budget can tolerate, it is recommended that two distinct links be acquired and tracked to increase the probability of maintaining at least one linkup between the EVA and SSF. When outage on one link is then experienced, the state vector positions from the remaining link are used to quickly reacquire a back-up.

The worst-case EVA/MMU mode demands a coarse sensor that rapidly reduces the full-spherical FOU to a value compatible with fast ACQ by the optical terminal, and subsequent re-establishment of fine tracking and communication. An extremely important element in the sensor design is that SSF continues to illuminate the EVA with a tight beacon, so that only a one-way reacquisition is necessary.

94

OPERATIONAL SCENARIO CONTROLS FOU

- Vehicles approaching SSF are acquired at 9-km, 37-km, or 2000-km range and tracked in; Geometry determines worst-case FOU (next slide)

- Vehicles docked at SSF are acquired just before leaving and tracked out, FOU is essentially zero

- FTS and MSC angular positions well-known (small SSF ACQ FOU); Coarse sensor described below potentially applicable for worst-case FTS/MSC FOU

- EVA/MMU acquired immediately after exiting SSF and tracked out and back; Two links acquired if weight budget allows; FOU is essentially zero

- If one EVA/MMU link is lost or obscured, positional information from the remaining link is used to reacquire a back-up

- If both EVA/MMU links are lost or obscured simultaneously, reacquisition becomes extremely difficult (spherical FOU in worst case)

    - SSF continues to have very accurate knowledge of astronaut's location

    - Coarse acquisition sensor that reduces the spherical FOU to a 1-degree FOU will allow rapid reacquisition

ACQUISITION FOU

This chart quantifies the ACQ FOU for the long-range vehicles entering the Prox-Ops zone. The acquisition process begins by the reception of input data on both SSF and the long-range vehicle as to the position of the other spacecraft. These positional inputs are assumed accurate to within ± 10 m along each axis. As shown, a simple analysis converts this positional uncertainty into a 2-mrad equivalent angular uncertainty. In addition, the boresight alignment uncertainty must be added to this value to determine the ACQ FOU. The FOU values used in the link analysis to follow are therefore 10 mrad on SSF and 20 mrad on the vehicle.

96

ACQUISITION FOU IS A KEY DESIGN DRIVER

- GPS assumed available on SSF, OMV, Shuttle, and co-orbiters

  - SSF and vehicle positions assumed known
    to within ± 10 m along each axis
  - At 9-km range, worst-case angular uncertainty is

$$\theta_p = \tan^{-1} (20/9000) = 2.2 \text{ mrad}$$

- Vehicle boresight alignment uncertainty
  assumed to be ± 0.5 deg

- Net vehicle FOU is (17 + 2.2) or 19.2 mrad;
  Analysis assumes FOU = 20 mrad for OMV, Shuttle,
  and co-orbiters

- SSF boresight alignment uncertainty assumed better
  than ± 0.5 deg; Analysis assumes SSF FOU = 10 mrad

97

ACQUISITION, TRACKING, AND COMMUNICATION ANALYSIS

The next series of charts give results of the ACQ, track, and COMM analyses for Prox-Ops. The acquisition analysis begins with a discussion of the various ACQ approaches, including fixed or scanning beacons and staring or scanning receivers. Optical link analyses are then performed with an assumed 50-mW laser power to determine beam sizes that provide acceptable SNR and probability of acquisition. The beam sizes are then used to estimate the corresponding ACQ times and gimbal scan rates. Similar link analyses are then performed for the tracking and communication subsystems to determine optical beamwidths that provide acceptable tracking accuracy and communication bit error rate (BER). In all cases, optical background effects are included in the analysis.

The analysis approach proposes a strawman system, assigns representative parameter values, and uses the analysis results to comment on and to formulate the three optical subsystem designs. The assumed parameter values are therefore not necessarily optimum, but instead the analysis serves to identify the difficulties associated with an optical Prox-Ops and to offer a representative solution. In addition, several shortcomings associated with a given detector selection are identified, and this is a particularly important consideration when attempting to combine ACQ, track, and COMM functions on a single detector.

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ACQUISITION, TRACKING, AND COMMUNICATION ANALYSIS

- Acquisition sequence: Scanning concepts, active/passive approaches, handoff to fine tracking

- Optical link budget: Determines laser power & beam spread for ACQ/TRK/COMM, acquisition time & scan mirror bandwidth, tracking requirements, detector requirements, optical background effects

- Approach: Propose and analyze strawman design; Assign representative parameter values

ACQUISITION SEQUENCE OPTIONS

The acquisition approaches are listed on this chart, and are essentially summarized as SSF with a fixed or scanning beacon, together with a vehicle receiver that either stares or scans. In all cases, SSF initiates acquisition by transmitting a beacon to the vehicle. The vehicle detects the SSF beacon, narrows its initial FOU, and points a narrow beacon compatible with fine-track and communication back towards the estimated SSF location. Ultimately, the vehicle illuminates SSF with its narrow beacon. SSF then quickly detects the vehicle beacon and points a narrower beacon at the vehicle to complete the mutual acquisition sequence. The key issues in the ACQ sequence selection become limited laser power, optical background effects on receive SNR, and beacon scan rates required to rapidly achieve (few seconds) mutual acquisition.

100

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ACQUISITION SEQUENCE OPTIONS

- Fixed beacon and staring receiver

- Scanning beacon and staring receiver

- Fixed beacon and scanning receiver

- Scanning beacon and scanning receiver

FIXED BEACON/STARING RECEIVER CONCEPT

The simplest acquisition approach uses two essentially passive optical terminals. A fixed SSF acquisition beacon is broadened to fill the 10-mrad FOU with a detectable power level at the vehicle. A 20-mrad null-to-null beamwidth is sufficient with the assumed 4-dB acquisition pointing loss. SSF also has a receiver that stares at the vehicle with a 10-mrad FOV, while the vehicle receiver stares at its 20-mrad FOU. The vehicle uses multiple detections (if necessary) of the fixed SSF beacon for FOU reduction, and points a narrow beacon back at SSF. SSF detects the vehicle beacon and returns its own narrower beacon to the vehicle to complete the mutual acquisition sequence.

Since FOU scanning is unnecessary, mutual acquisition is quickly achieved. However, this scheme is suitable only for very short ranges, because of laser power limitations that preclude large beamwidths. Further, beacon detections are hampered by the background power in the large receive FOVs that impacts the ability to achieve adequate SNR and high acquisition probability. This approach therefore has limited utility in Prox-Ops.

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FIXED BEACON AND STARING RECEIVER CONCEPT IN PROX-OPS

- SSF acquisition beacon floods 10-mrad area of uncertainty, and each terminal stares with FOV equal to its FOU (10-mrad for SSF, 20-mrad for vehicle)

  - Simple approach, SSF and vehicle are essentially passive
  - Vehicle detects SSF beacon, reduces FOU for compatibility with track/COMM, and returns narrow beacon to SSF
  - SSF detects vehicle beacon and returns narrow beacon to vehicle
  - Limited to short range by available laser power
  - Receiver performance limited by background noise

FOU

VEHICLE TERMINAL
FOV = FOU

FOU

SPACE STATION TERMINAL
FOV = FOU

103
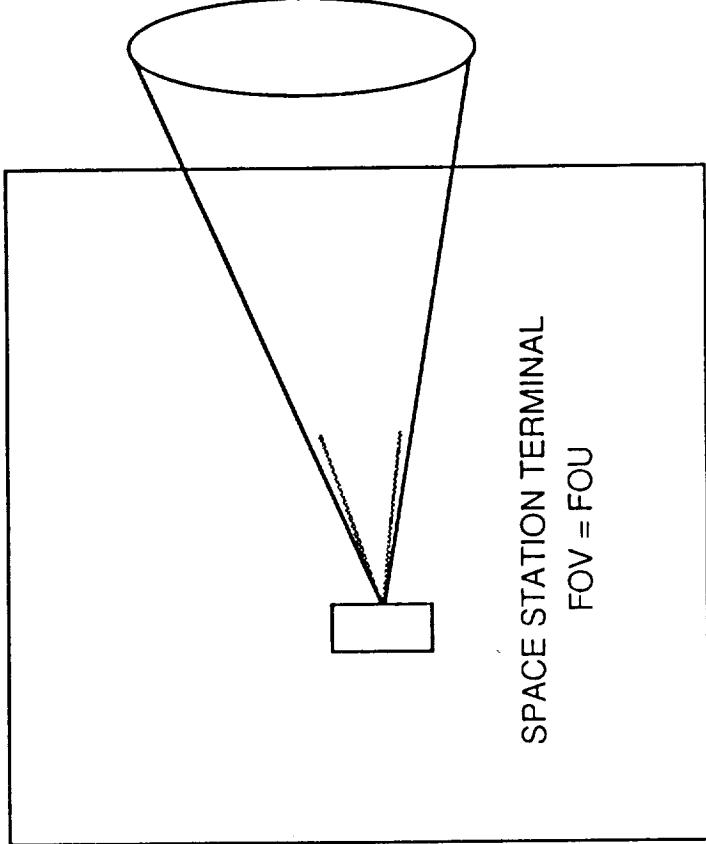
SCANNING BEACON/STARING RECEIVER CONCEPT

The second acquisition approach uses an active SSF terminal and essentially passive vehicle terminal. SSF and the vehicle first open-loop point at one another based on GPS position data. SSF initiates acquisition by scanning its beacon over the 10-mrad FOU, and scanning requirements are eased by using the broadest beam that supports the acquisition link budget. In most cases, the beamwidth must be later narrowed to support fine-track and communication. The vehicle stares with a 20-mrad FOV and detects the scanned SSF beacon. Depending on the detector type (more on this in a later chart), several detections of the scanned beacon are used on the vehicle to reduce the angular uncertainty in SSF 's position. After the appropriate number of detections, the vehicle points a narrow beacon compatible with fine-track and communication back at SSF. SSF detects the vehicle beacon, stops its scan, and points a narrow beacon at the vehicle that closes the fine-track and communication links.

SCANNING BEACON AND STARING RECEIVER CONCEPT IN PROX-OPS

- SSF beacon scans area of uncertainty, Vehicle acquisition receiver stares with full FOU, and vehicle points narrow beacon at center of SSF FOU

  - Vehicle detects scanned beacon, reduces FOU, and points its beacon at SSF
  - SSF detects vehicle beacon, stops scan, and points narrow beacon at vehicle
  - Beamwidth, scan time, and optical background are traded

FOU

VEHICLE TERMINAL
FOV = FOU

FOU

SPACE STATION TERMINAL

FOV = FOU

105
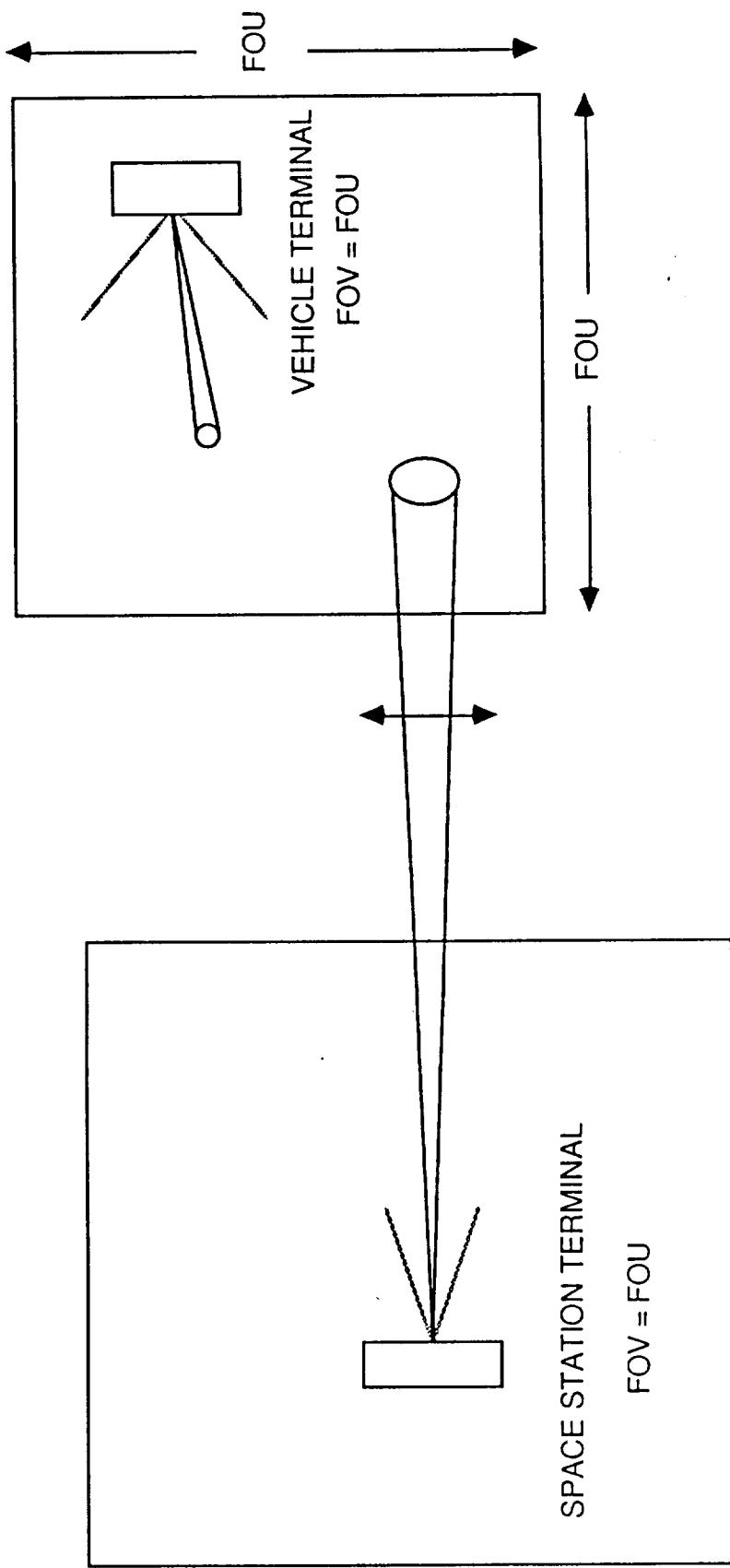
FIXED BEACON/SCANNING RECEIVER CONCEPT

This approach, essentially the reverse of that shown on the previous chart, involves an active vehicle terminal and passive SSF terminal. As in all acquisition sequences, the process begins with the two terminals open-loop pointing at one another based on GPS position data. SSF floods its FOU with a 20-mrad null-to-null beam, and the vehicle scans a narrow receive FOV over its 20-mrad FOU. Successive detections of the staring beacon are used on the vehicle to reduce the angular uncertainty in SSF's location. After adequate FOU reduction (e.g., receive spot centered on quad cell), the vehicle stops its scan and returns a narrow beacon compatible with track/COMM back to SSF. SSF detects the vehicle beacon, and narrows its transmit beacon for compatibility with fine-track and COMM to the vehicle.

106

FIXED BEACON AND SCANNING RECEIVER CONCEPT IN PROX-OPS

- SSF beacon points at full FOU while vehicle receiver scans its FOU

  - Vehicle detects fixed SSF beacon, reduces its FOU, stops scan, and points narrow beacon at SSF
  - SSF detects vehicle beacon and returns narrow beacon to vehicle
  - Narrow FOV reduces receiver background noise
  - Limited to short range by available laser power

FOU

VEHICLE TERMINAL
FOV < FOU

FOU

SPACE STATION TERMINAL
FOV = FOU

107
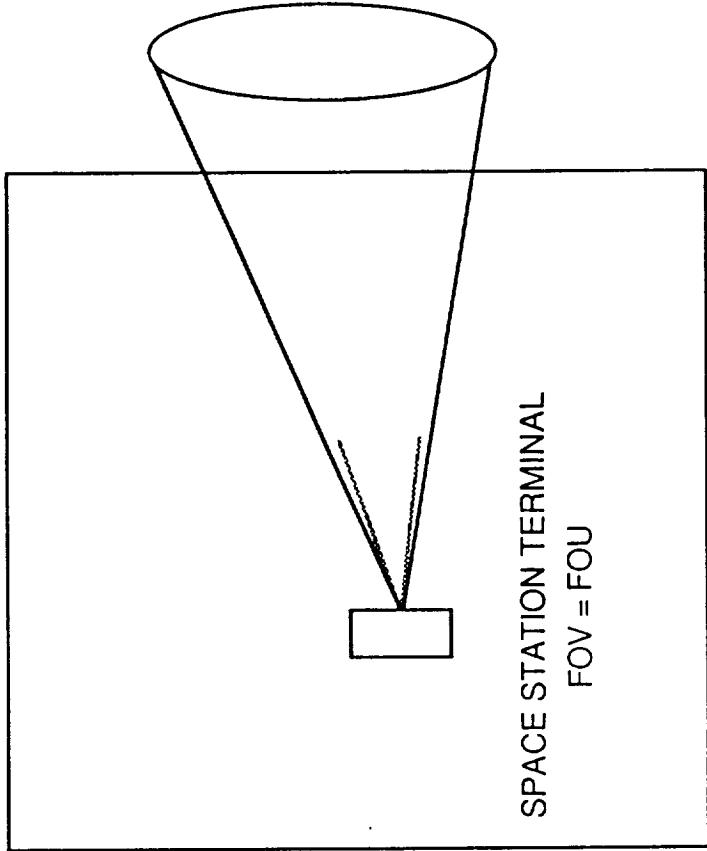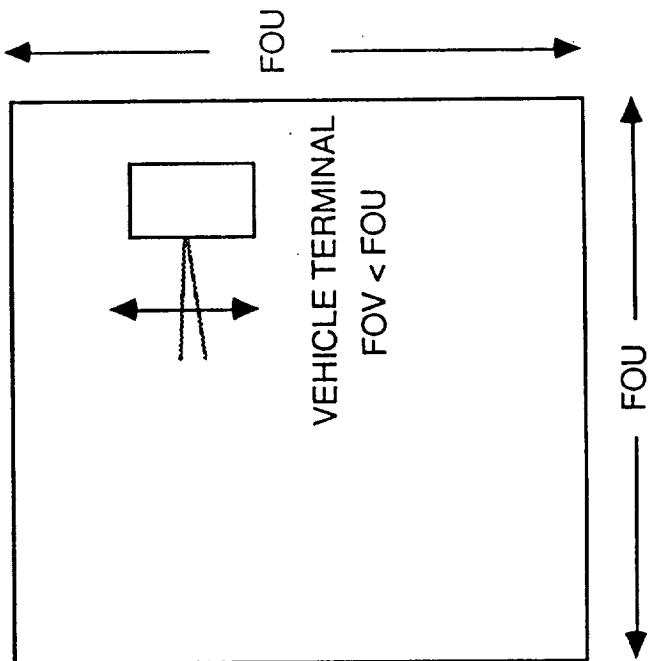
SCANNING BEACON/SCANNING RECEIVER CONCEPT

The most difficult acquisition approach involves two actively scanning terminals. Although this approach efficiently uses limited laser power and reduces receive background noise, the difficulties associated with coordination of the SSF and vehicle scans outweigh any advantages gained. Furthermore, the probability of acquisition is likely to suffer from these implementation difficulties. It is therefore not recommended for Prox-Ops.

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SCANNING BEACON AND SCANNING RECEIVER CONCEPT IN PROX-OPS

- SSF beacon and vehicle receiver scan their respective areas of uncertainty

  - Difficult implementation, Both terminals active
  - Scans must be coordinated to provide mutual coverage of both FOVs

FOU

VEHICLE TERMINAL
FOV < FOU

FOU

SPACE STATION TERMINAL

FOV = FOU
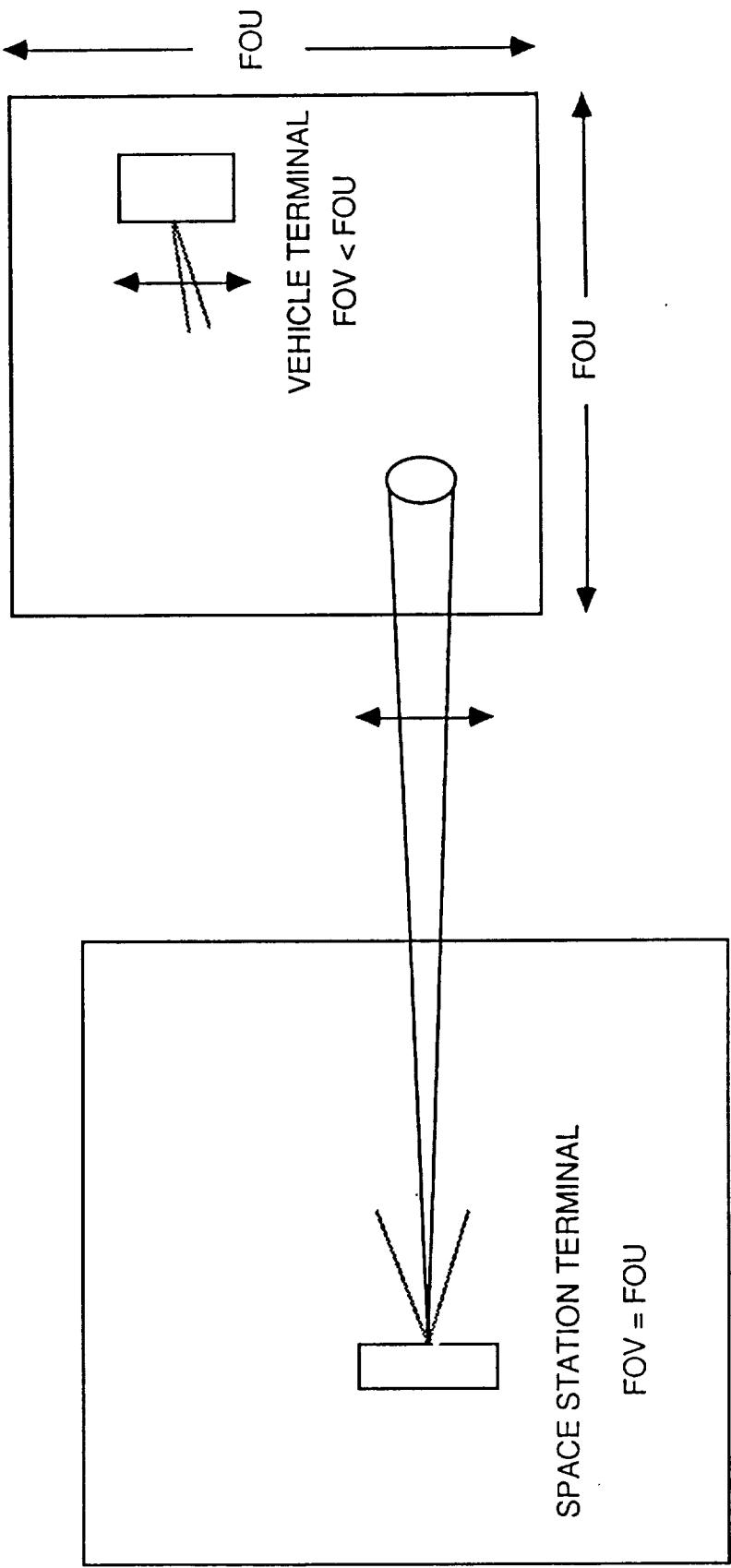
RECOMMENDED ACQUISITION APPROACH

Based on the foregoing discussions, the second approach is recommended for Prox-Ops, that uses a scanning SSF beacon and staring vehicle receiver. Reasons for this choice are listed on the chart, and power budget analyses are required to determine the beam sizes, scan rates, and acquisition times associated with this selection. These results are discussed on the next several charts.

110

SCANNING BEACON AND STARING RECEIVER APPROACH IS RECOMMENDED

- Laser power more limiting than background shot noise

- SSF active, vehicle essentially passive

- Converges to fixed-beacon, staring-receiver approach for short ranges

- Power budget analysis defines detailed acquisition sequence

OPTICAL LINK BUDGET TRADEOFFS

The next several charts provide detailed results on performance analyses for the Prox-Ops long- and short-range ACQ, track, and COMM subsystems. The analysis uses the standard range equation described elsewhere   which relates receive power and resultant signal-to-noise ratio at the detector, to the power from the transmitter that has been reduced by the various system losses. As discussed earlier, direct-detection receivers are assumed throughout, and several detectors are compared in each of the three subsystems to quantitatively assess their suitability. This process also uncovers the tradeoffs involved with using a single detector approach in Prox-Ops versus the more traditional three-detector approach. An important item in the analysis is the effect of optical background on subsystem performance; the details of this various background sources have been described on a previous chart. Finally, the assumed link parameters are shown.

Derived design parameters include ACQ time, track beamwidth, effect of solar background on track performance, and communications beamwidth that achieves the desired BER. The communications analysis assumes the well-established binary pulse position modulation (BPPM) format, and a transimpedance receiver preamplifier that sacrifices sensitivity (2 to 3 dB) compared to a high-impedance front end, but provides a higher dynamic range that eases the automatic gain control (AGC) provisions needed to accommodate the large Prox-Ops range variations (discussed on a later chart).

112

OPTICAL LINK BUDGET TRADEOFFS

- Range equation analysis assumes direct-detection receivers

- 50-mW GaAlAs diode laser source at 830 nm

- Several detectors compared to determine suitability of single-detector approach

- CW and modulated track beacon approaches compared to determine applicability of tracking off the COMM beam

- BPPM communications format; 10^{-6} average BER; Transimpedance receiver front end sacrifices sensitivity for larger dynamic range

- Earth background up to 9 km, Venus and Moon background up to 37, 2000 km

- Generic parameters

  - Transmit telescope optical efficiency = 0.5
  - Receive telescope optical efficiency = 0.5
  - Telescope obscuration ratio = 0.33 for 10-cm
    0 for 1-cm (refractive)

  - Point-ahead loss = 0 dB at short range
    0.5 dB at long range

  - Bandpass filter width = 25 A
  - Link margin = 4 dB

113

LONG-RANGE LINK DESIGN

Link budget results are provided in this section for the long-range Prox-Ops ACQ, track, and COMM subsystems. As discussed earlier, these design results are applicable to SSF, OMV, STS, and co-orbiting platforms for both the initial (37-km range) and growth (2000-km range) phases. Beginning with the acquisition subsystem, ACQ times and gimbal scan rates are determined for the scanning SSF beacon and staring vehicle receiver approach. Fine-tracking analyses are then discussed which determine transmit optical beamwidths that maintain adequate tracking accuracy in the presence of typical platform disturbances and receive optical backgrounds. Tracking requirements are alleviated by spreading the beam as much as the link budget will allow. The system impact of maintaining fine-tracking in the presence of a solar background is then discussed. This is desirable since its eliminates the need for reacquisition following a solar communications outage, but is found to require a separate track detector with a small FOV to reduce background shot noise. Finally, communications analyses are completed to determine transmit optical beamwidths that provide the desired bit error rate on both SSF and the vehicles.

114

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LONG-RANGE LINK DESIGN

- Acquisition analysis

  – Beam size, acquisition time, scan rate

- Fine tracking analysis

  – Beam size with and without a solar background

- Communication analysis

  – Beam size

- Results applicable to SSF (10-mrad FOU) and OMV, Shuttle, co-orbiters (20-mrad FOU)

LONG-RANGE ACQUISITION ANALYSIS

This chart summarizes the long-range ACQ subsystem analyses and baseline parameter assumptions. As shown, a variety of acquisition detectors were analyzed to allow a comparison between the baselined quadrant-detector and more-traditional, charge-transfer-array approaches. Results obtained in this section are used on a later chart to select an appropriate ACQ detector, with the corresponding SSF ACQ beamwidth and SSF gimbal scan rate that provide fast acquisition for the assumed FOUs and despite expected optical backgrounds.

116

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LONG-RANGE ACQUISITION ANALYSIS

- 50-mW SSF beacon scans 10-mrad FOU, vehicle receiver stares at 20-mrad FOU

- SSF beam size and corresponding acquisition time determined for

  - PIN quadrant cell
  - Avalanche quadrant cell
  - CCD array
  - CID array

  on vehicle with 20-mrad FOV

- 10-cm aperture on SSF and vehicle

- Probability of acquisition = 0.99, 10-ms integration time

117

LONG-RANGE ACQUISITION BEAM SIZE RATIO

Shown on this chart are calculated acquisition beam size ratios (BSR) for various detector and beacon combinations. The BSR is defined relative to the diffraction-limited transmit beamwidth; BSR = 1 corresponds to a diffraction-limited (full Airy beamwidth) transmit beam. Based on the 10-cm SSF aperture, a BSR of 1000 corresponds to a 20-mrad Airy disk transmitted to the vehicle, sufficient to flood the 10-mrad SSF FOU with a detectable power on the vehicle (4-dB acquisition pointing loss assumed). For BSR greater than 1000, it is therefore prudent to set BSR at 1000 and flood the FOU, corresponding to the fixed beacon, staring receiver ACQ approach. For those cases with BSR less than 1, the acquisition link is not supported with the assumed transmitter power and aperture diameters; either of these parameters must be increased to use these approaches under these conditions. Note that the optical design with the assumed commercially available RCA avalanche quadrant detector requires f/0.75 to support the 20-mrad FOV requirement; equivalently, this detector can only support a 15-mrad FOV with a 10-cm, f/1 optical design.

A variety of results are included in this table, based on expected optical background sources for the different links. For ranges up to 9-km, the largest background source (excluding the Sun) is the sunlit Earth. Beyond that range, an earlier chart has shown the Prox-Ops communication zones and indicated that the Earth is no longer in either the SSF or vehicle FOVs, i.e., communication is basically in a plane parallel to the Earth's surface. The key background sources then become the Moon for quadrant detectors and Venus for the array detectors. Results for both these background sources have been included at 37-km and 2000-km ranges.

Conclusions reached from the results include: (1) A quadrant detector supports Prox-Ops acquisition, (2) Charge-transfer arrays clearly offer superior acquisition performance and are therefore often baselined for this application, (3) CCD arrays offer the best ACQ performance, owing to their reduced readout noise compared to CIDs, (4) A modulated beacon improves performance for an extended background source (Earth and Moon), but not for a point background source (Venus), (5) Point background sources limit the array detector performance because of the narrow pixel FOV.

118

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BEAM SIZE RATIO (BSR) RESULTS FOR LONG-RANGE ACQUISITION

Detector	Beacon type	BSR @			
		R = 9 km	R = 37 km		R = 2000 km
PIN quad cell	CW 10-kHz SIM	22.6 1744	947.4 / 25.4 489 / 484.7		17.5 / 0.47 9.0 / 9.0
Avalanche quad cell	CW 10-kHz SIM	39.1 3375	2132 / 44.0 3999 / 1676		39.5 / 0.81 74 / 31
CCD array	CW	10340	2568 / 5086		47.5 / 94.1
CID array	CW	6342	1554 / 1816		28.8 / 33.6

Transmit D = 10 cm, BSR = 1000 ⟶ 20-mrad Airy disk @ 830 nm
BSR < 1 ⟶ Far-field power density must be increased to give BSR = 1
BSR > 1000 ⟶ Set SSF BSR = 1000 and flood 10-mrad FOU
Background: Earth @ 9 km; Venus / Moon @ 37 km and 2000 km

APPROXIMATION OF ACQUISITION TIME

The BSR results on the previous chart and the equations shown on this chart are used to estimate the ACQ times and gimbal scan rates for the various cases. FOU scanning is viewed as a series of segments, with the 0.48 factor included to account for the overlap required to assure a detectable power level at each point in the FOU (raster scan without holes). Search time is estimated by summing the times required to cover the FOU, allowing multiple detections at each scan site to account for the FOU reduction that ultimately has the narrow vehicle return beacon pointed directly at SSF. The scan rate is simply the ratio of the effective transmit beam size and the total detection time.

For the sake of this study, acquisition time is set equal to the search time calculated from these equations. Two points should be noted. First, since the scan rate is adjusted to allow multiple detections before moving on to the next scan site, this is a worst-case estimate of ACQ time in most cases, as it allows the multiple detections to be performed at the last site. Second, if the detections actually occur at the last scan site, the actual ACQ time would be somewhat larger than this estimate to allow for detection on both SSF and the vehicle of the returned narrow beacons. However, this difference would be insignificant with the assumed 10-msec receiver update time.

120

ACQUISITION TIME CAN BE APPROXIMATED

- # scan segments = $(\theta_{unc} / \beta \theta_s)^2$

  θ_{unc} = field of uncertainty = 10 mrad for scanning SSF beacon

  β = 1 for receiver

  = 0.48 for Airy beam

  θ_s = beam size = $2.44 \lambda (BSR) / D_t$ for transmitter

  = FOV for receiver

- Search time = $M_T M_R N \tau$

  M_T = # beacon scan segments

  M_R = # receiver scan segments = 1 for staring vehicle receiver

  N = # detections necessary for acquisition $\approx \left\{ \begin{array}{l} \text{8 to 10 for quad cell} \\ \text{1 for charge transfer array} \end{array} \right.$

  τ = receiver update time = 10 msec

- Scan rate = $\beta \theta_s / (N \tau)$

LONG-RANGE LINK ACQUISITION TIME

Shown are the long-range ACQ times calculated using information on the two preceding charts. The results indicate that fast ACQ (several seconds or less) is achievable with the proposed sequence, except under worst-case background conditions in the growth-phase. In the latter case, transmitter power limitations impact the design, thus demanding an alternate acquisition approach (discussed further on a later chart).

122

ACQUISITION TIME FOR LONG-RANGE LINKS

Detector	Beacon type	Acq time (sec), Scan rate (mrad/s)		
		R = 9 km	R = 37 km	R = 2000 km
PIN quad cell	CW	207, 2.2	< 0.5, 92 / 164, 2.5	346, 1.7 / --
	10-kHz SIM	< 0.5, N/A	< 0.5, 47.5 / < 0.5, 47.1	1307, 0.9
Avalanche quad cell	CW	70, 3.8	< 0.5, N/A / 55, 4.3	68, 3.8 / --
	10-kHz SIM	< 0.5, N/A	< 0.5, N/A	20, 7.2 / 111, 3
CCD array	CW	< 0.5, N/A	< 0.5, N/A	4.7, 46.2 / 1.2, 91.5
CID array	CW	< 0.5, N/A	< 0.5, N/A	12.8, 30 / 9.4, 32.7

Background: Earth @ 9 km; Venus / Moon @ 37 km and 2000 km

LONG-RANGE FINE TRACKING ANALYSIS

This chart summarizes the analyses completed to determine optical beamwidths required to close the fine tracking links under a variety of conditions. Compared are performances for quadrant detectors with both CW and modulated beacons, and a 2 by 2, CID subarray (the CID array would then be used as the ACQ detector) that is operated like a quadrant detector to detect a CW track beacon. The CW beacon approaches are preferred since they allow tracking off the receive communications beam. Otherwise, separate track lasers and detectors are required at both link ends. The receive SNR is arbitrarily set at 10, since previous experience has shown this sufficient to reduce the track-detector-noise contribution to the tracking error (otherwise known as the noise equivalent angle) to acceptable (microradian) levels . Of academic interest, with the rather broad beams that support the Prox-Ops links, this assumption may result in a fine-tracking performance that is somewhat better than required to provide acceptable burst error performance. However, the steepness of the SNR vs performance function indicates this to be a minor factor. Tracking performance is characterized for the two detector update rates shown, thus trading off the track subsystem bandwidth and platform disturbance rejection capability with the optical beamwidth that supports the link budget.

The analysis assumes that tracking is maintained out to the burst error angle, where the communications link no longer maintains synchronization. For the average BER assumed in this analysis, the burst error angle is approximately 4 dB below the peak of the receive Airy profile (i.e., corresponding to a 4-dB pointing loss in the link budget assessments).

124

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LONG-RANGE FINE TRACKING ANALYSIS

- 50-mW track laser on SSF and vehicle

- SSF FOV = 10 mrad
  Vehicle FOV = 20 mrad

- Analysis determines SSF and vehicle beam sizes

  - PIN and avalanche quadrant detectors
    with CW and modulated beacons
  - CID subarray with CW beacon

- 10-cm aperture on SSF and vehicle

- Receive signal-to-noise ratio = 10 dB (voltage);
  20 dB (power)

- Detector update time = 0.2 msec, 1 msec

BEAM SIZE RATIO FOR 5-kHz SSF FINE TRACKING

This chart summarizes the BSR results for the fine tracking link from the vehicle to SSF, with a 5-kHz SSF-detector update rate. A quad cell can support the track link, but a modulated beacon approach is needed at the longest range to combat the Moon background in the 10-mrad FOV required to support mutual acquisition. The CID subarray approach assumes that a full 256 by 256 CID array is used to stare at the 10-mrad acquisition FOU, and the 2 by 2 subarray is operated like a quadrant detector to perform fine tracking. This approach provides the best tracking performance, due the efficient background discrimination provided by the small pixel FOV (39.1 μrad in this example). However, the CID ACQ/track detector selection has other consequences. For example, although appearing feasible at this time, development and testing will be required to use the CID for detection of the 0.5-Mbps vehicle communication signal. Regardless, this selection demands separate SSF ACQ/track and COMM (25-Mbps rate) detectors that increases payload complexity and SWAP.

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BEAM SIZE RATIO (BSR) RESULTS FOR 5-kHz LONG-RANGE TRACKING ON SSF

Detector	Beacon type	BSR @		
		R = 9 km	R = 37 km	R = 2000 km
PIN quad cell	CW 10-kHz SIM	45.1 605.3	256.3 / 25.3 153.8 / 152.5	4.7 / 0.5 2.8 / 2.8
Avalanche quad cell	CW 10-kHz SIM	78.2 1466	1427 / 43.9 1245 / 526.5	26.4 / 0.8 23.0 / 9.7
CID subarray	CW	2745	668.3 / 680.6	12.4 / 12.6

10-mrad FOV, 0.2-msec update time

Background: Earth @ 9 km; Venus/Moon @ 37 km and 2000 km

BEAMWIDTH FOR SSF 5-kHz SSF SSF FINE TRACKING

The BSR results on the previous chart are used to calculate the null-to-null beamwidths for the SSF 5-kHz track link. These results are used on a later chart for comparison with the appropriate COMM beamwidths.

128

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BEAMWIDTH REQUIREMENTS FOR 5-kHz LONG-RANGE TRACKING ON SSF

Detector	Beacon type	Full Beamwidth (mrad) @		
		R = 9 km	R = 37 km	R = 2000 km
PIN quad cell	CW 10-kHz SIM	0.91 12.3	5.2 / 0.51 3.1 / 3.1	0.095 / -- 0.057 / 0.057
Avalanche quad cell	CW 10-kHz SIM	1.58 29.7	28.9 / 0.89 25.2 / 10.7	0.53 / -- 0.47 / 0.20
CID subarray	CW	55.6	13.5 / 13.8	0.25 / 0.26

10-mrad FOV, 0.2-msec update time

Background: Earth @ 9 km;   Venus/Moon @ 37 km and 2000 km

129

BEAM SIZE RATIO FOR 1-kHz SSF FINE TRACKING

BSR results are provided for a 1-kHz track link from the vehicle to SSF. Compared to the previous 5-kHz results, this track system trades platform-disturbance-rejection capability with the optical beamwidth that closes the fine-tracking link. The improvement is insignificant for the quad cell/CW approaches with large receive BG (Earth and Moon cases), but is rather significant for the quad cell/modulated beacon and CID subarray cases. Nonetheless, because of the unknown nature of the various platform disturbance spectra, the 5-kHz track data will be carried forth in this report; the 1-kHz results are provided for reference purposes and will be useful should future assessments indicate this approach suitable for Prox-Ops.

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BEAM SIZE RATIO (BSR) RESULTS FOR 1-kHz LONG-RANGE TRACKING ON SSF

Detector	Beacon type	BSR @		
		R = 9 km	R = 37 km	R = 2000 km
PIN quad cell	CW 10-kHz SIM	45.2 905.2	491.2 / 25.4 230.1 / 228	9.1 / 0.5 4.3 / 4.2
Avalanche quad cell	CW 10-kHz SIM	78.2 2193	1761 / 44 1874 / 788	32.6 / 0.8 34.7 / 14.6
CID subarray	CW	7449	1826 / 2140	33.8 / 39.6

10-mrad FOV, 1-msec update time

Background: Earth @ 9 km; Venus/Moon @ 37 km and 2000 km

BEAM SIZE RATIO FOR 5-kHz VEHICLE FINE TRACKING

This chart summarizes the BSR results for the fine tracking link from SSF to the long-range vehicle, with a 5-kHz vehicle-detector update rate. Results similar to those discussed on the previous 5-kHz chart apply. For the quadrant detector cases, only those results at 9-km range have changed compared to that earlier chart, since the appropriate background sources at the longer ranges subtend less than a 10-mrad angle. The CID subarray cases are different at all ranges because the 256 by 256 full CID array now stares at a 20-mrad acquisition FOU, resulting in a 78.1-μrad pixel FOV.

BEAM SIZE RATIO (BSR) RESULTS FOR 5-kHz LONG-RANGE TRACKING ON VEHICLE

Detector	Beacon type	BSR @		
		R = 9 km	R = 37 km	R = 2000 km
PIN quad cell	CW	22.6	256.3 / 25.3	4.7 / 0.5
	10-kHz SIM	548.6	153.8 / 152.5	2.8 / 2.8
Avalanche quad cell	CW	39.1	1427 / 43.9	26.4 / 0.8
	10-kHz SIM	1062	1245 / 526.5	23.0 / 9.7
CID subarray	CW	2563	625.7 / 669.1	11.6 / 12.4

20-mrad FOV, 0.2-msec update time

Background: Earth @ 9 km; Venus/Moon @ 37 km and 2000 km

133

BEAMWIDTH FOR 5-kHz VEHICLE FINE TRACKING

The BSR results on the previous chart are used to calculate the null-to-null beamwidths for the vehicle 5-kHz track link. These results are used on a later chart for comparison with the appropriate COMM beamwidths.

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BEAMWIDTH REQUIREMENTS FOR 5-kHz LONG-RANGE TRACKING ON VEHICLE

Detector	Beacon type	Full Beamwidth (mrad) @		
		R = 9 km	R = 37 km	R = 2000 km
PIN quad cell	CW 10-kHz SIM	0.46 11.1	5.2 / 0.51 3.1 / 3.1	0.095 / -- 0.057 / 0.057
Avalanche quad cell	CW 10-kHz SIM	0.79 21.5	28.9 / 0.89 25.2 / 10.7	0.53 / -- 0.47 / 0.20
CID subarray	CW	51.9	12.7 / 13.6	0.23 / 0.25

20-mrad FOV, 0.2-msec update time

Background: Earth @ 9 km; Venus/Moon @ 37 km and 2000 km

BEAM SIZE RATIO FOR 1-kHz VEHICLE FINE TRACKING

BSR results are provided for a 1-kHz track link from SSF to the long-range vehicle. As for the track links to SSF, compared with the previous 5-kHz vehicle track link results, platform-disturbance-rejection capability and optical beamwidths that close the link are traded. The improvement is again insignificant for the quad cell/CW approaches with large receive BG (Earth and Moon cases), but rather significant for the quad cell/ modulated beacon and CID subarray cases. As before, because of the unknown nature of the various platform disturbance spectra, only 5-kHz tracking results are carried forth in this study; the 1-kHz results are provided for reference purposes only.

BEAM SIZE RATIO (BSR) RESULTS FOR 1-kHz LONG-RANGE TRACKING ON VEHICLE

Detector	Beacon type	BSR @		
		R = 9 km	R = 37 km	R = 2000 km
PIN quad cell	CW 10-kHz SIM	22.6 820.4	491.2 / 25.4 230.1 / 228	9.1 / 0.5 4.3 / 4.2
Avalanche quad cell	CW 10-kHz SIM	39.1 1588	1761 / 44 1874 / 788	32.6 / 0.8 34.7 / 14.6
CID subarray	CW	5144	1270 / 1842	23.5 / 34.1

20-mrad FOV, 1-msec update time

Background: Earth @ 9 km; Venus/Moon @ 37 km and 2000 km

LONG-RANGE TRACKING WITH SOLAR BACKGROUND

The system impact of maintaining track in the presence of a solar background is assessed on this chart. Tracking through the solar background eliminates the need to reacquire after a solar-conjunction communications outage, but, as shown on this chart, demands a separate solar track detector in Prox-Ops. This results from the wide FOV needed to support mutual acquisition, combined with the design approach that attempts to use the same detector for ACQ, track, and COMM. As shown, a detector FOV of some several hundred microradians is needed to reduce the receive solar background and allow adequate tracking during solar conjunction. Because of the need for a separate detector and its corresponding payload impact, solar tracking is probably not warranted for Prox-Ops, and instead fast reacquisition should be performed immediately after the solar outage period. Finally, because of the small pixel FOV, it might be possible to achieve both normal and solar tracking using a CID subarray, but the detector performance and saturation effects must be carefully assessed.

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OPTION: LONG-RANGE TRACKING THROUGH A SOLAR BACKGROUND

- Limited receiver dynamic range implies solar background saturates quadrant track detector with 10-mrad FOV (background power approximately 10 mW with 10-cm aperture)

- (Separate) detector with much smaller FOV required to track a modulated beacon through the solar background (CID subarray of potential use with CW beacon, but must consider performance, saturation, etc.)

- Assume 1.5-mm PIN quadrant detector with 1-msec update time and 10-kHz SIM beacon

FOV (μ rad)	f (m)	SOLAR BG POWER (μ W)	Full Beamwidth (mrad) at R = 9 km	Full Beamwidth (mrad) at R = 2000 km	RECEIVED BEACON POWER (nW)
150	10	2.7	13.1	0.059	2.3
300	5	10.7	9.7	0.043	4.2
750	2	67	6.2	0.028	10.3
1500	1	268	4.4	BSR < 1	20.6

139

COMMUNICATIONS BEAMWIDTH TO SSF

This chart summarizes the communications subsystem beamwidths required for 25-Mbps transmission to SSF at the design BER. The quadrant-detector results account for the optical background received in the 10-mrad SSF detector FOV. The PIN- and avalanche-photodiode results do not include background effects, and are provided only to allow comparison with a COMM system tailored to its specific needs that has a small FOV and insignificant receive background (except during solar conjunction). The results show that the quad cell can support Prox-Ops return COMM requirements, but a power-limited situation is emerging at 2000-km range; this is also the case with the photodiode detectors having small FOV. These COMM beamwidths demand tracking accuracies of one-twentieth of the transmit beamwidth to avoid high burst error rates and thus provide reliable communications. This demands microradian tracking accuracies at the longest range; approaching the requirements for a typical long-range, high-data-rate laser communication system.

The results in this table assume 10-cm apertures on both link ends, with 14-dB composite additional link losses to account for transmit and receive obscurations and optical absorption, point ahead, tracking error, and design link margin. Specific parameter values were discussed on an earlier chart.

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TRANSMIT BEAMWIDTH FOR LONG-RANGE COMMUNICATION TO SSF AT 25 Mbps

SSF Detector	Received Signal Power	Full Beamwidth (mrad) for R =		
		9 km	37 km	2000 km
PIN quadrant detector (10-mrad FOV)	48 nW @ 9 km 45 nW @ 37, 2000 km	4.3	1.05	0.020 (BSR < 1)
Avalanche quadrant detector (10-mrad FOV)	7.3 nW @ 9 km 3.7 nW @ 37, 2000 km	11.1	3.8	0.070
PIN photodiode	36 nW (6000 photons/bit)	5.0	1.2	0.022
Avalanche photodiode	1.8 nW (300 photons/bit)	22.3	5.4	0.10

10-cm receive aperture, Tracking accuracy ≤ (Transmit beamwidth) / 20 (0.5-dB loss) req'd
Background in 10-mrad FOV = 142 nW (Earth) @ 9 km, 26.5 nW (Moon) @ 37, 2000 km

COMMUNICATIONS BEAMWIDTH TO VEHICLE

This chart summarizes the communications subsystem beamwidth requirements for 0.5-Mbps transmission to the vehicle at the design BER. Similar to the corresponding SSF chart, the quadrant-detector results account for the optical backgrounds received in the 20-mrad vehicle detector FOV. The PIN- and avalanche-photodiode results again do not include background effects, and are provided to allow comparison with a COMM system tailored to its specific needs that has small FOV and insignificant receive background (except during solar conjunction). The results show that the quad cells can also support the Prox-Ops forward COMM requirements, with a power-limited situation again emerging at 2000-km range. Note that this conclusion also follows for the photodiode detectors with small FOV. However, the beamwidth requirements for both are not as demanding as for data reception on SSF because of the lower vehicle receive data rate. The COMM beamwidths again demand tracking accuracies of one-twentieth of the transmit beamwidth to avoid high burst error rates and providereliable communications. These demands are approaching microradian tracking accuracies at the longest range.

The results in this table again assume 10-cm apertures at both link ends and 14-dB composite additional link losses.

142

TRANSMIT BEAMWIDTH FOR LONG-RANGE COMMUNICATION TO VEHICLE AT 0.5 Mbps

Vehicle Detector	Received Signal Power	Full Beamwidth (mrad) for R =		
		9 km	37 km	2000 km
PIN quadrant detector (20-mrad FOV)	1.8 nW @ 9 km 1.1 nW @ 37, 2000 km	22.7	6.9	0.125
Avalanche quadrant detector (20-mrad FOV)	1.5 nW @ 9 km 420 pW @ 37, 2000 km	24.5	11.3	0.21
PIN photodiode	720 pW (6000 photons/bit)	35.3	8.6	0.16
Avalanche photodiode	50 pW (300 photons/bit)	134	32.6	0.60

10-cm receive aperture, Tracking accuracy $\leq$ (Transmit beamwidth) / 20 (0.5-dB loss) req'd
Background in 20-mrad FOV = 567 nW (Earth) @ 9 km, 26.5 nW (Moon) @ 37, 2000 km

SHORT-RANGE ANALYSIS SUMMARY

This chart summarizes the analysis results for the short-range Prox-Ops links that, as described earlier, apply to the FTS, MSC, and EVA/MMU. As expected, the short range removes any optical power limitations and allows use of a 1-cm aperture on the vehicle that reduces payload weight.

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SHORT-RANGE LINK ANALYSIS SUMMARY

- Applicable to FTS, MSC, and EVA/MMU links

- Fast acquisition achieved with scanning SSF beacon and 20-mrad vehicle FOV

  - At 1-km range, respective acquisition times of 2 and 0.7 sec for integrating PIN and avalanche quad cell approaches
  - Quad cells with modulated beacon, CCD array, or CID array support fixed SSF beacon, staring vehicle receiver approach up to 1-km range
  - All detectors support fixed SSF beacon, staring vehicle approach for FTS and MSC (200-m maximum range); Integrating PIN quad cell approach is simplest
  - Coarse acquisition sensor required to handle worst-case EVA/MMU scenario (design to follow)

- PIN quad cell and CW beacon achieves adequate fine tracking at 1-km range through Earth background

  - Track off communication beam
  - 4.5-mrad null-to-null beamwidth supports vehicle track link
  - 10.6-mrad beamwidth supports SSF track link

SHORT-RANGE TRACKING WITH SOLAR BACKGROUND

The system impact of tracking through a solar background is assessed for the short-range links on this chart. SSF performance is assessed because of its larger receive aperture; the effect is reduced on the vehicle, but a separate solar track detector is also likely needed to eliminate the marginal dynamic range situation experienced there. Tracking through the solar background eliminates the need to reacquire after a solar-conjunction communications outage, but is shown to demand a separate solar track detector in Prox-Ops. This again results from the wide FOV needed to support mutual acquisition, combined with the desire to perform ACQ, track, and COMM with the same detector. As shown, a detector FOV of some several hundred microradians is needed to reduce the receive solar background and allow adequate tracking. Because of the need for a separate detector and its corresponding payload impact, solar tracking is probably not warranted in Prox-Ops, and instead fast reacquisition should be performed immediately after the solar outage period. Finally, because of the small pixel FOV, it might be possible to again perform both normal and solar tracking with a CID subarray, but the performance and saturation effects must be carefully assessed.

146

OPTION: SHORT-RANGE TRACKING THROUGH A SOLAR BACKGROUND

- Limited receiver dynamic range implies solar background saturates quadrant track detector with 10-mrad FOV and 10-cm aperture (background power approximately 10 mW); Marginal situation with 1-cm aperture and 20-mrad FOV

- (Separate) detector with much smaller FOV required to track a modulated beacon through the solar background (CID subarray of potential use with CW beacon, but must consider performance, saturation, etc.)

- Assume 1.5-mm PIN quadrant detector with 1-msec update time, and 10-kHz SIM beacon, 1-cm transmit aperture, 10-cm receive aperture

FOV (μ rad)	f (m)	SOLAR BG POWER (μ W)	Full Beamwidth (mrad) at R =1 km	RECEIVED BEACON POWER (nW)
150	10	2.7	150.7	2.3
300	5	10.7	111.4	4.2
750	2	67	71.5	10.3
1500	1	268	50.6	20.6
3000	0.5	1073	35.8	41.1

COMMUNICATION BEAMWIDTH TO SSF

This chart summarizes the communications beamwidth requirements for 25-Mbps transmission to SSF at the design BER. The quadrant-detector results account for the optical backgrounds received in the 10-mrad SSF detector FOV. The PIN- and avalanche-photodiode results do not include background effects, and are provided to allow comparison with a COMM system tailored to its specific needs that has small FOV and insignificant receive background (except during solar conjunction). The results show that the quad cell can easily support the short-range Prox-Ops return COMM requirements. The COMM beamwidths again demand tracking accuracies of one-twentieth of the transmit beamwidth to avoid high burst error rates, and these are readily achieved for the short-range links. If desired, the tracking error can be reduced below one-twentieth of the transmit beamwidth to essentially eliminate the small tracking error loss (0.5 dB assumed), but this provides a fairly insignificant change in the COMM beamwidths. The major benefit in so doing is that the diode laser transmitter can be operated at a reduced output power, thereby reducing drive power and extending its lifetime.

The results in this table assume 10-cm and 1-cm apertures on SSF and the vehicle, respectively, with composite additional link losses of 11.5 dB to account for transmit and receive optical absorption losses, receive telescope obscuration, tracking error, and design link margin.

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TRANSMIT BEAMWIDTH FOR SHORT-RANGE (1 km) COMMUNICATION TO SPACE STATION AT 25 Mbps

SSF Detector	Received Signal Power	Full Beamwidth (mrad)
PIN quadrant detector (10-mrad FOV)	48 nW	52.0
Avalanche quadrant detector (10-mrad FOV)	7.3 nW	133.4
PIN photodiode	36 nW (6000 photons/bit)	60.0
Avalanche photodiode	1.8 nW (300 photons/bit)	268.6

10-cm receive aperture,   Background in 10-mrad FOV = 142 nW (Earth)

COMMUNICATION BEAMWIDTH TO VEHICLE

This chart summarizes the communications beamwidth requirements for 0.5-Mbps transmission to the vehicle at the design BER. Similar to the preceding SSF chart, the quadrant-detector results account for the optical backgrounds received in the 20-mrad vehicle detector FOV. The PIN- and avalanche-photodiode results do not include background effects, and are provided to allow comparison with a COMM system tailored to its specific needs that has small FOV and insignificant receive background (except during solar conjunction). The results show that the quad cell can readily support the Prox-Ops forward COMM requirements. The beamwidths are narrower than those on SSF because of the smaller vehicle aperture. The COMM beamwidths again demand tracking accuracies of one-twentieth of the transmit beamwidth to avoid high burst error rates, and this is readily achieved at such short-ranges. If desired, the small tracking loss is again essentially eliminated by operating with a better tracking accuracy than specified above.

It is worth noting that these beamwidth requirements can be used to determine the laser count for the hemispherical SSF source approach. Hemispherical coverage with this approach demands 9320 SSF-based lasers for PIN-quad-cell detection on the vehicle, and 1960 SSF-based lasers with an avalanche quad cell detector on the vehicle.

The results in the table assume 10-cm and 1-cm apertures on SSF and the vehicle, respectively, with 13.5-dB composite additional losses to account for transmit and receive optical absorption, transmit obscuration, tracking error, and design link margin.

TRANSMIT BEAMWIDTH FOR SHORT-RANGE (1 km) COMMUNICATION TO VEHICLE AT 0.5 Mbps

Vehicle Detector	Received Signal Power	Full Beamwidth (mrad)
PIN quadrant detector (20-mrad FOV)	950 pW	29.3
Avalanche quadrant detector (20-mrad FOV)	200 pW	64.0
PIN photodiode	720 pW (6000 photons/bit)	33.7
Avalanche photodiode	50 pW (420 photons/bit)	128

1-cm receive aperture,   Background in 20-mrad FOV = 5.7 nW (Earth)

TRACK/COMM BEAMWIDTH COMPARISON

The table summarizes the beamwidth requirements for the Prox-Ops fine-tracking and communication links, assuming the baselined 50-mW diode laser transmitter and PIN quadrant receiver. The tracking link always drives the design when the preferred CW beacon approach is used that allows tracking off the communications beam. The reasons behind this are that the communications data rates are much smaller than in typical laser communications systems, the track link is designed to operate out to the burst error angle where the communications link loses synchronization, and the CW beacon approach is inefficient with large receive backgrounds, since the SNR must be established above the background photon count. From the perspective of link losses, the tracking-link pointing loss is 4 dB, whereas the COMM-link pointing loss is on order 0.5 dB, provided the tracking accuracy is at the specified one-twentieth of the transmit beamwidth or better.

At 2000-km range, power-limited conditions are realized in the return communications link. Either the vehicle transmitter power and/or aperture must be increased or the SSF aperture must be increased to close the COMM link. Quantitatively, an 80-mW transmitter power and 10-cm aperture on both link ends will close the COMM link with a 1.25X diffraction-limited transmit beamwidth. Alternatively, 13-cm apertures on both the vehicle and SSF could be used with a 50-mW diode. With these selections, the CW track link will remain power-limited, so that further increases in transmitter power and/or aperture are required to support the preferred tracking approach. The payload impact of the preferred CW approach must be compared with the impact of using a separate modulated track beacon that also entails separate track and COMM detectors.

Finally, for those links that are not power-limited, it is recommended that the tracking subsystem operate at even narrower beamwidths than calculated and shown here. This operating mode can be supported by the FSM/quadrant detector combination baselined for Prox-Ops [1], and allows further reductions in diode transmitter power that ease implementation and extend life.

FINE-TRACKING AND COMMUNICATION BEAMWIDTH SUMMARY

- The following optical beamwidths (in mrad) are required to close the appropriate links with a 50-mW diode and PIN quadrant detector

Host Vehicle	Track Beamwidth	COMM Beamwidth
SSF		
R = 1 km	10.6 (CW)	52.0
R = 9 km	0.91 (CW), 12.3 (SIM)	4.3
R = 37 km	0.51 (CW), 3.1 (SIM)	1.05
R = 2000 km	-- (CW), 0.057 (SIM)	--
Long-range vehicle		
R = 9 km	0.46 (CW), 11.1 (SIM)	22.7
R = 37 km	0.51 (CW), 3.1 (SIM)	6.9
R = 2000 km	-- (CW), 0.057 (SIM)	0.125
Short-range vehicle (R = 1km)	4.5 (CW)	29.3

- In most cases, the track beamwidth drives the design

- At 2000-km range, the transmit power and/or aperture must be increased to close the return communication link. At this range, the CW tracking method is inadequate without further increases in transmit power and/or aperture

  – Implies separate track and COMM lasers
  – Separate track and COMM detectors also needed to independently detect the SIM and BPPM signals

WORST-CASE SHORT-RANGE TERMINAL DESIGN

The system design described thus far is sufficient for normal conditions, where the operational scenario reduces the vehicle acquisition FOU to 20 mrad or less. However, a worst-case scenario can be envisioned whereby this reduced FOU is unachievable, particularly for the EVA/MMU. This worst-case condition is best accommodated by supplementing the previous design with a coarse acquisition sensor that reduces the full FOU to a value that is easily handled by the laser terminal acquisition subsystem. As shown, this sensor must rapidly reduce a full-spherical FOU to approximately 10 to 20 mrad, and thereby allow acquisition in no more than a few seconds. The key element in the design, and the only reason such a largeFOU can be rapidly reduced to a 10 to 20 mrad level, is that SSF is assumed to always illuminate the vehicle with a narrow beacon. The acquisition process is thus only one way. A second key element in the sensor design is that the Sun will necessarily be in the receive FOV, thus requiring a modulated beacon approach for efficient background discrimination. Because of this, it might be prudent to baseline the optical terminal acquisition process around the same modulated beacon approach, to minimize the complexity in handover between the coarse-sensor and acquisition subsystems. Finally, although the sensor is specifically designed to accommodate the worst-case EVA/MMU conditions, its applicability might well extend to all short-range Prox-Ops links, and to the antenna handover sequence needed to cope with expected LOS obscurations

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COMMENTS ON WORST-CASE (EVA/MMU) SHORT-RANGE TERMINAL DESIGN

- Previous calculations indicate fast acquisition (< 1 sec), accurate tracking (suitable burst error probability), and reliable communications (10^{-6} BER) are achievable up to 1-km range if the vehicle FOU is 20-mrad or less

    - Valid for FTS and MSC (normal operating conditions), or when at least one bidirectional link is maintained between EVA/MMU and SSF

- Difficult reacquisition requirement emerges when all communications to EVA/MMU are interrupted

    - Under worst-case conditions, EVA has no knowledge of SSF location (full-spherical FOU)
    - SSF continues to have very accurate knowledge of EVA location and illuminates EVA with a tight beacon
    - Coarse acquisition sensor required to reduce EVA spherical FOU to about 20-mrad, and allow laser system to rapidly reacquire (1 or 2 links depending on weight allowance)
    - Coarse sensor must accommodate solar background, modulated beacon required for this mode

- The coarse sensor may have general use in the short-range Prox-Ops link acquisition sequence, and for the antenna handover sequence that copes with anticipated LOS obscurations

155

DETECTOR CUBE SOLVES WORST-CASE REACQUISITION

This chart shows our concept for a coarse sensor capable of satisfying the requirements described on the previous chart. Several coarse sensors are likely required on the vehicle to cover a full-spherical FOU despite shadowing effects, and this can be accomplished with minimal SWAP impact due to the compactness of the sensor design.

The basic operation of the device is as follows. The received signal from three pairs of opposing detectors (two each for the x,y,z directions) are compared using "greatest of" detection to reduce the FOU from a full sphere to a hemisphere. Further FOU reduction within the hemisphere is accomplished by using the direction cosines determined with the simple equations provided at the bottom of the chart. In these equations, the photocurrents on the three designated orthogonal faces are processed to compute the angular coordinates of the receive SSF beacon. These coordinates are handed off to the laser terminal acquisition subsystem for further FOU reduction, and subsequent establishment of fine tracking and communications.

The next several charts assess both the qualitative and quantitative aspects of the coarse sensor in Prox-Ops. It is beyond the scope of this effort to fully assess the coarse sensor for this application, but rather first-cut assessments are provided that indicate the design soundness. Further in-depth assessments are required and recommended as follow-on efforts to determine the sensor's true applicability, including a "field-test" under solar background conditions. During the course of this study, a proof-of-concept laboratory demonstrator was fabricated and tested to verify the basic operating features described on the next several charts.

DETECTOR CUBE SOLVES WORST-CASE REACQUISITION

Flux seen by any face is reduced from normal incidence by factor of

$$\vec{S} \cdot \vec{n}$$
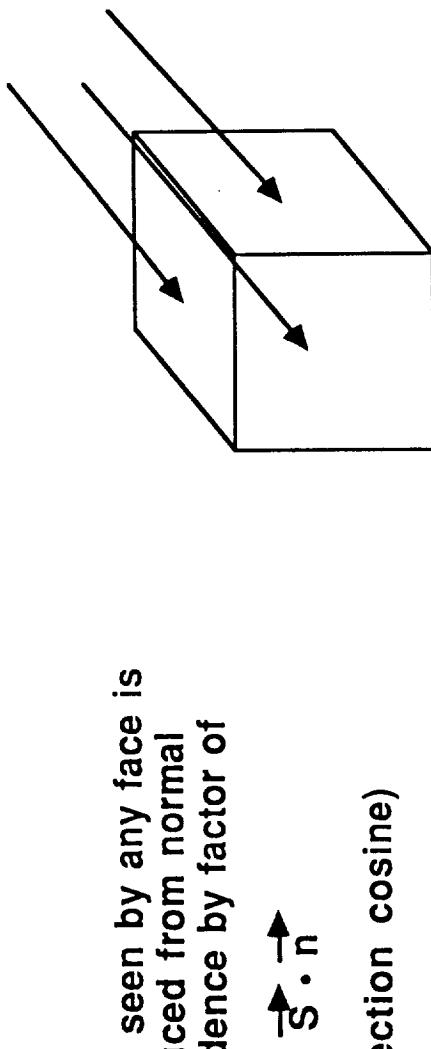
(direction cosine)

Using three pairs of opposing detectors (x,y,z directions), the vector components of the received optical beam are determined using the direction cosines

$$\vec{S} \cdot \vec{x} = \frac{i_x}{\sqrt{i_x^2 + i_y^2 + i_z^2}}$$

$$\vec{S} \cdot \vec{y} = \frac{i_y}{\sqrt{i_x^2 + i_y^2 + i_z^2}}$$

$$\vec{S} \cdot \vec{z} = \frac{i_z}{\sqrt{i_x^2 + i_y^2 + i_z^2}}$$

DETECTOR CUBE CHARACTERISTICS

The qualitative characteristics of the detector cube sensor are indicated on this chart. The key item is the inherent simplicity of the concept that results in a lightweight and power-efficient device. An item for concern is whether the beacon angular coordinates can be determined within the 10 to 20 mrad range under all incident angles. The particularly stressing situation is expected at extreme grazing incidence of either of the facets, where the receive antenna pattern could result in a significantly reduced signal level. Several comments apply here. First, a coating must be applied to the detector facets to avoid specular reflection. Second, at extreme grazing incidence, very sensitive phase-locking detection techniques should be applicable and are expected to provide the necessary angular sensitivity. Exploration of such sensitive detection methods is recommended as a follow-on effort to prove the suitability of the coarse sensor. This assessment is probably best performed as a simulated field test that includes a solar optical background.

Finally, because of shadowing effects, a single six-sided cube is likely not sufficient under all possible incidence angles. Two cubes rigidly mounted on opposite sides of the vehicle should minimize these effects and allow rapid FOU reduction.

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DETECTOR CUBE CHARACTERISTICS

- Cube geometry provides simple processing algorithm (direction cosines)

- Specular reflection avoided at grazing incidence by imparting a Lambertian characteristic surface at detector

- If shown necessary, lock-in detection techniques (phase-sensitive detection) can be investigated to extract small signals from noise under extreme grazing incidence — Recommended follow-on effort

- Rigidly mounting two cubes on opposite sides of vehicle/astronaut minimizes eclipsing effects

REACQUISITION LINK BUDGET

This chart shows the quantitative considerations for the coarse acquisition sensor. Neglecting the extreme incidence condition described on the previous chart that would best be assessed in a field test, the worst-case finds the receive modulated beacon at 45 degrees to each cube surface. Under these conditions, determination of the beacon angular position to within 10 mrad requires about a 0.25-sec integration time with a 10-mW effective SSF laser power that illuminates the 10-mrad SSF FOU. The 10-mrad condition allows margin for using the laser terminal acquisition subsystem already shown capable of quickly acquiring in a 20-mrad FOU. The 10-mW effective transmitter power requires a 50-mW diode in the SSF focal plane, based on typical optical absorption and obscuration losses. With this same transmitter power, resolution to within 20 mrad (remove handover margin) results in a 60-msec integration time. In either case, the net 1-sec reacquisition time applies, based on the previous ACQ time results at 1-km range.

EVA/MMU REACQUISITION LINK BUDGET

- Worst-case scenario has receive modulated beacon at 45 degrees to each cube surface (neglecting extreme grazing incidence condition)

- With this incidence angle,

$$\frac{\Delta i_s}{\Delta \theta} \approx \left. \frac{d\, i_s}{d\theta} \right|_{\theta=45} = \left. \frac{d}{d\theta} (A \cos \theta) \right|_{\theta=45} = \left. A \sin \theta \right|_{\theta=45} = \left. \sqrt{2}\, A \right|_{\theta=45} = i_s$$

  this implies $\quad \Delta i_s = i_s \cdot \Delta \theta = i_s / 100$

- An rms noise current $i_n < i_s / 100$ is needed to resolve the angular position of the incident beam to within 10 mrad

  $$\left(\frac{S}{N} \right)_i = 100 \quad \text{implies} \quad \left(\frac{S}{N} \right)_p = (100)^2 = \frac{\eta \, P_S^2 \, \tau}{h\nu \, (P_S + P_B)}$$

- 10-mW effective transmit power into 10-mrad beam implies 100-nW signal power on an 8-cm^2 detector, 800-mW background power (Sun) on same detector

  $$h\nu = 2.4 \times 10^{-19} \text{ J} \;\; ; \;\; \eta = 0.8$$

- Required integration time to barely resolve 10 mrad is

  $$\tau = 0.25 \text{ sec}$$

- Implies EVA/MMU reacquisition time on order 1 sec

161

SPECIFIC REACQUISITION LINK BUDGET

This chart specifically quantifies the coarse acquisition sensor performance, indicating an approximate 3-dB link margin to determine the SSF beacon position to within 10 mrad with a 0.5-sec sensor integration time. Fast reacquisition conditions (total ACQ time on order 1 sec) are still met under these conditions. Although presented specifically for the demanding EVA/MMU case, the results shown here are applicable to all short-range links, including the docking long-range vehicles (STS and OMV) and the FTS/MSC.

SPECIFIC REACQUISITION LINK BUDGET

(SSF to EVA/MMU: 1-km range, 0.83-μm wavelength)

Average transmitter power (50 mW)	+ 17 dBm
Transmit optics loss	- 3 dB
Transmit telescope obscuration loss (Primary/Secondary = 3)	- 2.6 dB
Transmit telescope gain (10-mrad FWHM)	+ 51.7 dB
Range loss	- 71.0 dB
Receive signal power density	- 7.9 dBm/m^2
Receive optical background power density (100 mW/cm^2)	+ 60 dBm/m^2
Receiver integration time	0.5 sec
Receive signal-to-noise ratio (8-cm^2 detector)	45.4 dB
Required receive SNR to resolve within 10 mrad	40 dB
Required receive signal power density	-10.6 dBm/m^2
Link margin	+ 2.7 dB

CONCLUSIONS OF ACQUISITION ANALYSIS

This chart summarizes the acquisition subsystem performance. The initial-phase acquisition requirements are satisfied by using a PIN quadrant detector on the vehicle (20-mrad FOV) to detect a modulated SSF beacon. Other alternatives satisfy the requirements, but impact the system complexity and SWAP. For the growth-phase Prox-Ops, the PIN quad approach demands greater than a 50-mW transmitter power and/or larger than 10-cm apertures to combat the large optical backgrounds in the 20-mrad receive FOV. Such requirements begin to have significant impact on the payload complexity and SWAP; the separate-detector approach for ACQ and Track/COMM has similar consequences. The preferred approach in this case is to reduce the FOU, if at all possible, to values typically assumed for many laser communication systems. Reduction to about ± 0.1 degree (3.5-mrad FOU) allows acquisition scanning with the fast steering mirror in the terminal focal plane, and has been shown capable of providing fast acquisition over even longer ranges [5].

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CONCLUSIONS OF ACQUISITION ANALYSIS

- For long-range links

  - Fast acquisition (<1 sec) achieved in initial phase (R = 37 km), using modulated beacon and PIN quadrant detector
  - Fast ACQ also achieved at 37-km range using a CW beacon and charge transfer array detector, but likely entails separate detectors on vehicle for ACQ and TRK/COMM
  - To achieve fast acquisition in the growth phase (R = 2000 km),
    - -- The CW beacon/CCD array approach provides 5-sec ACQ time, but entails two detectors to meet ACQ and TRK/COMM
    - -- Or, the far-field power density and/or vehicle aperture can be increased, but the design is necessarily more complex and has larger SWAP
    - -- Or, an alternate acquisition approach is needed - Reduced FOU allows SSF FSM to scan near-diffraction-limited beacon and minimize coverage time

- For short-range links

  - Fast acquisition achieved with 20-mrad vehicle FOU, CW or modulated SSF beacon, and PIN quadrant detector
  - CW approach is simplest, but modulated beacon is more compatible with with coarse acquisition process

- EVA/MMU requires coarse acquisition sensor to accomodate worst-case scenario; Concept also useful for short-range coarse acquisition, if system constraints dictate

ACQUISITION SEQUENCE

The next four charts detail the Prox-Ops acquisition sequence, based on the scanning beacon/staring receiver approach. In all cases, SSF initiates acquisition by scanning its 10-mrad FOU. Scanning requirements are reduced by using the broadest possible beam that provides the desired signal-to-noise ratio at the vehicle receiver. For several of the short-range links, a 50-mW diode can flood the vehicle FOU making SSF scanning unnecessary. The vehicle always stares with a 20-mrad receive FOV, and points a narrow beacon (compatible with track/COMM) at the center of its FOU. If dictated by the system constraints, a coarse sensor on the vehicle can be used to reduce the initial vehicle FOU to 20 mrad.

ACQUISITION SEQUENCE

(1) In general, Space Station terminal scans vehicle area of uncertainty. Scanning requirements alleviated using the broadest beacon that supports the link budget. In some cases, FOU is small enough and range short enough that a 50-mW SSF diode can illuminate the entire area with a detectable power level. For such short-range situations, a detector cube on the vehicle determines SSF's position to within a 20-mrad FOU. Vehicle terminal stares at the 20-mrad FOU, and points narrow beacon at its center.

FOU

VEHICLE TERMINAL
FOV = FOU

FOU

SPACE STATION TERMINAL
FOV = FOU
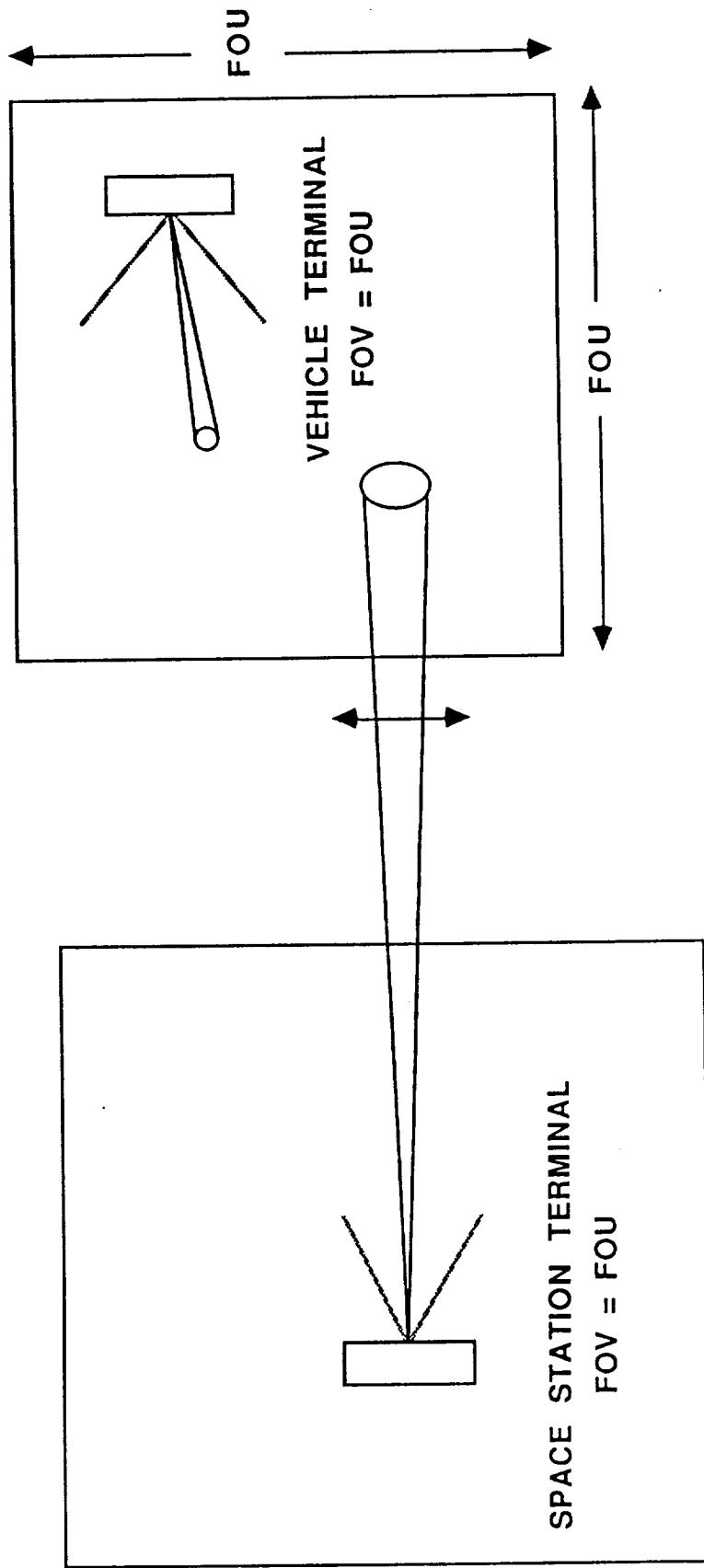
ACQUISITION SEQUENCE (cont.)

In the second stage, the vehicle detects the light pulse from SSF as it sweeps across it FOV, and performs pointing error correction to point its tight beacon back to the estimated SSF location. Depending on the vehicle detector type, multiple detections could be necessary for sufficient FOU reduction, and, as described earlier, the SSF beacon scan is slowed to allow these multiple detections before the beacon leaves the vehicle FOV. SSF continues to scan, looking for a return vehicle beacon.

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ACQUISITION SEQUENCE (cont.)

(2) Vehicle detects light pulse as Station beacon sweeps, and returns narrow beacon compatible with tracking and communication towards estimated location of Station. Station continues scanning its beacon; scan rate adjusted to allow multiple vehicle detections for FOU reduction.

VEHICLE TERMINAL FOV = FOU

SPACE STATION TERMINAL FOV = FOU

FOU

FOU
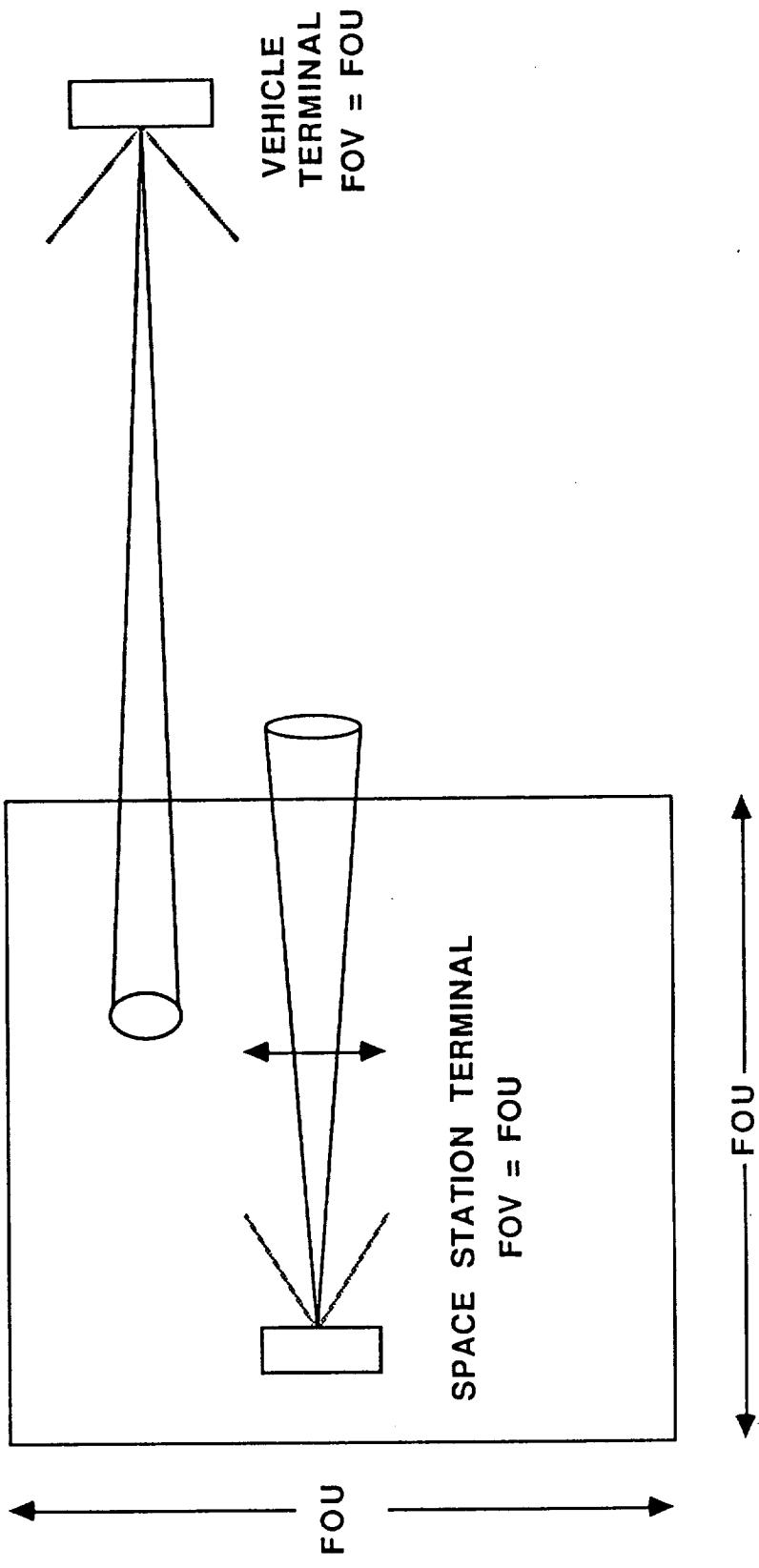
ACQUISITION SEQUENCE (cont.)

In the next stage, the vehicle uses multiple detections of the SSF beacon (as necessary) to reduce its estimate of SSF's location. SSF continues to scan, looking for a return vehicle beacon. After the appropriate number of detections (determined by the vehicle detector type), the vehicle FOU is sufficiently reduced that the narrow vehicle beacon points directly at SSF.

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ACQUISITION SEQUENCE (cont.)

(3) Successive detections of Station's beacon reduce pointing error of vehicle return beacon. After a sufficient number of detections (8 to 10 for a quadrant acquisition detector, 1 for a CCD or CID acquisition array), the vehicle beacon is pointed directly at Station.

VEHICLE TERMINAL

FOV = FOU

SPACE STATION TERMINAL

FOV = FOU
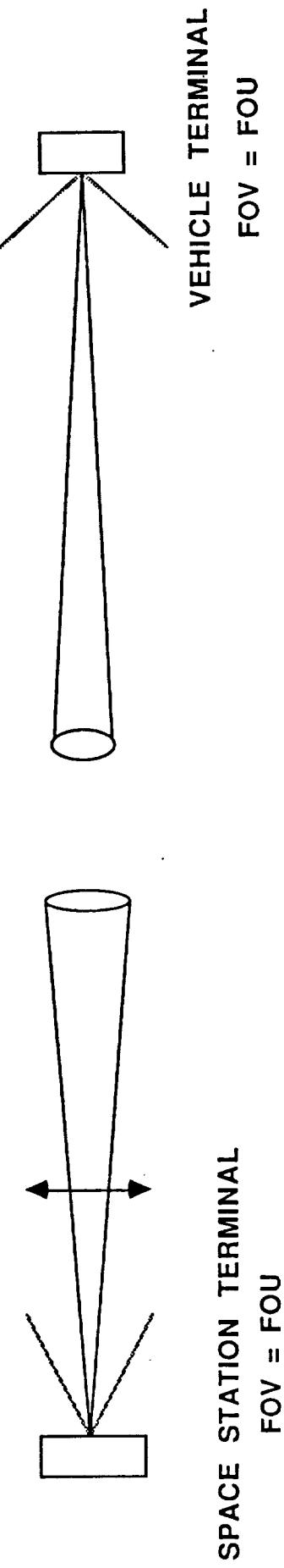
ACQUISITION SEQUENCE (cont.)

In the final stage, SSF detects the return vehicle beacon, and stops its scan. The SSF acquisition receiver then requires one scan of its 10-mrad FOU to locate the vehicle beacon, and to point a narrow beacon back at the vehicle. This completes the mutual acquisition process, and both terminals proceed to fine tracking and communications.

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ACQUISITION SEQUENCE (cont.)

(4) Vehicle beacon causes Space Station acquisition detector output to exceed a predetermined threshold level. Station terminal stops its beacon scan, narrows its beacon for compatibility with track/COMM, and uses one scan of vehicle FOU to locate vehicle beacon. Station then accurately points the narrow beacon at the vehicle and mutual acquisition is achieved. The quadrant detectors in each terminal proceed to mutual tracking and communications.

VEHICLE TERMINAL

FOV = FOU

SPACE STATION TERMINAL

FOV = FOU

173
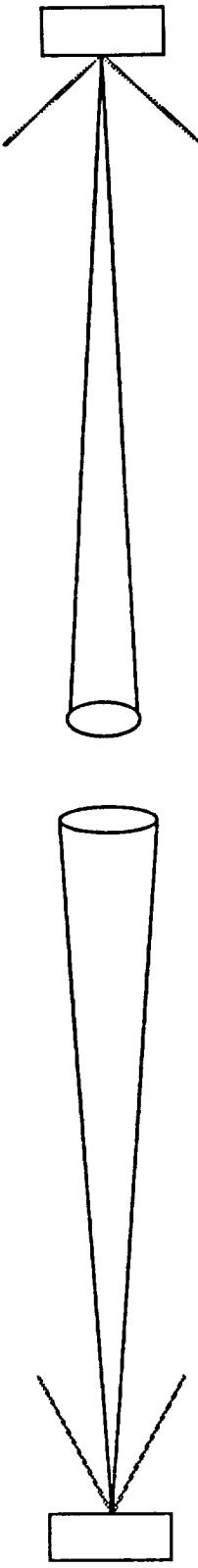
CONCLUSIONS OF FINE-TRACKING ANALYSIS

This chart summarizes the fine-tracking subsystem analysis, indicating the suitability of a PIN quadrant detector in Prox-Ops. The initial-phase system allows the CW track beacon approach, thus affording tracking off the received communications beam, and allowing single track/COMM lasers and detectors on both SSF and the vehicle. The growth-phase system is power-limited by the large background in the 20-mrad vehicle FOV, requiring a modulated track beacon approach that entails separate track and COMM lasers on SSF and the vehicle. The CID subarray approach could potentially reduce the vehicle terminal complexity, but its selection would require demonstration of a 0.5-Mbps communications capability.

Finally, tracking through a solar background eliminates the need for reacquisition after a solar-conjunction communications outage, but requires a separate track detector with narrow FOV to reduce the receive background. This increases the terminal complexity and SWAP, and since Prox-Ops acquisition is quickly achieved when the Sun is not in the receive FOV, the associated added complexity is probably not warranted.

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CONCLUSIONS OF TRACKING ANALYSIS

- Adequate performance provided by PIN quad cell with 20-mrad FOV (except for solar background)

- CW beacon approach sufficient up to R = 37 km (allows tracking off received communication beam)

- Modulated beacon required with PIN quad at R = 2000 km to combat Moon background in 20-mrad FOV

  - Separate track path (laser and detector)
  - CID subarray track detector allows CW approach

- Tracking achievable through a solar background using a modulated beacon and a (separate) PIN quadrant detector with a smaller FOV

175

CONCLUSIONS OF COMMUNICATION ANALYSIS

This chart summarizes the communication subsystem performance. Initial-phase communications requirements are satisfied by using a 50-mW diode laser transmitter and PIN quadrant detector on both SSF and the vehicle. For the growth-phase Prox-Ops, this approach again becomes power-limited in the return links because of the large backgrounds in the 10- and 20-mrad receive FOVs required to support acquisition, and demands greater than a 50-mW transmitter power and/or larger than 10-cm apertures. The forward link can be supported with the baseline selections due to its lower data rate.

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CONCLUSIONS OF COMMUNICATION ANALYSIS

- Initial phase long- and short-range communication achieved using a 50-mW diode and a PIN quadrant detector with a 20-mrad FOV

- Growth-phase (R = 2000 km) vehicle communication achieved with a 50-mW diode (125-μrad beam divergence) and PIN quadrant detector

- Growth-phase SSF communication requires higher far-field power density from vehicle, larger SSF receive aperture, or a separate COMM path to combat the Moon background

177

4.0 GIMBAL CONFIGURATION AND ANGULAR COVERAGE

This section describes Prox-Ops gimbal configurations that provide the necessary angular coverage. Two-axis and three-axis gimbals are first compared, trading off gimbal complexity and weight against angular coverage. The 10-cm and 1-cm systems are separately discussed, with the latter considering the tradeoff between the traditional gimballed-telescope approach and a gimballed-terminal approach considered attractive because of the smaller aperture. The weight of both the 1- and 10-cm gimbal systems are also assessed. Finally, detailed sketches of the Prox-Ops gimbals are provided.

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4.0 GIMBAL CONFIGURATION AND ANGULAR COVERAGE

- Two-axis vs three-axis gimbals

- Gimballed telescope vs gimballed terminal

- Gimbal weight assessment

- Gimbal sketches

- Spatial tracking configurations

GIMBAL CONFIGURATIONS FOR PROX-OPS

This chart summarizes the key elements that influence the Prox-Ops gimbal designs, and provides preliminary selections that meet the objectives. The primary requirement is for full hemispherical coverage, as the Prox-Ops system demands essentially outage-free communication over a full sphere. Based on the system design trades in Section 2.0, a gimballed transceiver approach was selected to minimize payload complexity and SWAP. The short-range vehicle terminals have been baselined around 1-cm optics, small enough that gimballing the entire focal plane is a viable option. The selection between this approach and a gimballed telescope is driven by system weight, since this is the prime concern for the vehicle terminals.

180

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GIMBAL CONFIGURATIONS FOR PROX-OPS

- Desirable Prox-Ops gimbal features

  - Full-hemispherical coverage
  - Low weight and complexity

- 10-cm gimballed telescope selected
  for SSF and long-range vehicles

- 1-cm gimballed telescope and gimballed
  terminal traded for short-range vehicles

  - Selection driven by payload weight

10-cm GIMBAL FEATURES

This chart summarizes the 10-cm gimbal design considerations, with an eye towards the desirable features of hemispherical coverage and low weight/complexity. Due to the expected focal-plane-assembly weight with 10-cm optics, a gimballed telescope with Coude' optical path is the prudent choice. With regard to angular coverage, a more-complex and heavier three-axis approach is required on SSF to support the full-hemispherical coverage requirement. As shown by the last bullet, the two-axis design could be useful for some Prox-Ops vehicles, but entails separate designs throughout the system. The designs in this report will therefore assume the 6.5-kg, three-axis gimballed telescope on both SSF and the long-range vehicles (STS, OMV, co-orbiters). Besides, the weight savings realized with the two-axis design is estimated to be at most a few pounds, hardly significant enough to warrant separate designs for SSF and the pertinent vehicles.

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10-cm GIMBAL FEATURES

- Gimballed telescope w/ Coude' optical path minimizes weight

- Two-axis design cannot provide necessary angular coverage

  - Gimbal lock results from mechanical acceleration limitations
  - Precludes coverage of 10° cone along outer axis

- Three-axis gimbal avoids lock cones

  - Full-hemispherical coverage
  - Spherical coverage limited only by gimbal-mount and vehicle interference
  - Increased complexity and weight compared to two-axis design

- Conclusions

  - Angular coverage demands three-axis design on SSF
  - Two-axis design potentially useful for some vehicles, but design commonality issues likely to drive selection towards three-axis gimbals throughout Prox-Ops
  - Three-axis, 10-cm gimballed telescope weight estimated at 6.5 kg

TWO-AXIS GIMBAL AND ANGULAR COVERAGE

This chart shows an artist's conception of a two-axis gimbal (actually being built by Ball for a separate laser communications application) and its associated angular coverage. Note the approximately 10-degree gimbal-lock cones where coverage is precluded. This uncovered area would be crucial in the Prox-Ops mission (consider the EVA/MMU or docking long-range vehicle, for example), making it an unacceptable choice on SSF at the very least. As referred to earlier, the two-axis approach could be of use for some of the Prox-Ops links (FTS, MSC, vehicles remaining at long ranges), but its selection is precluded by design commonality issues.

TWO-AXIS GIMBAL AND ANGULAR COVERAGE

Outer
axis
motion

Inner
axis
motion

Gimbal
lock
cone

Gimbal motion

Inner axis
drive

Outer axis
drive
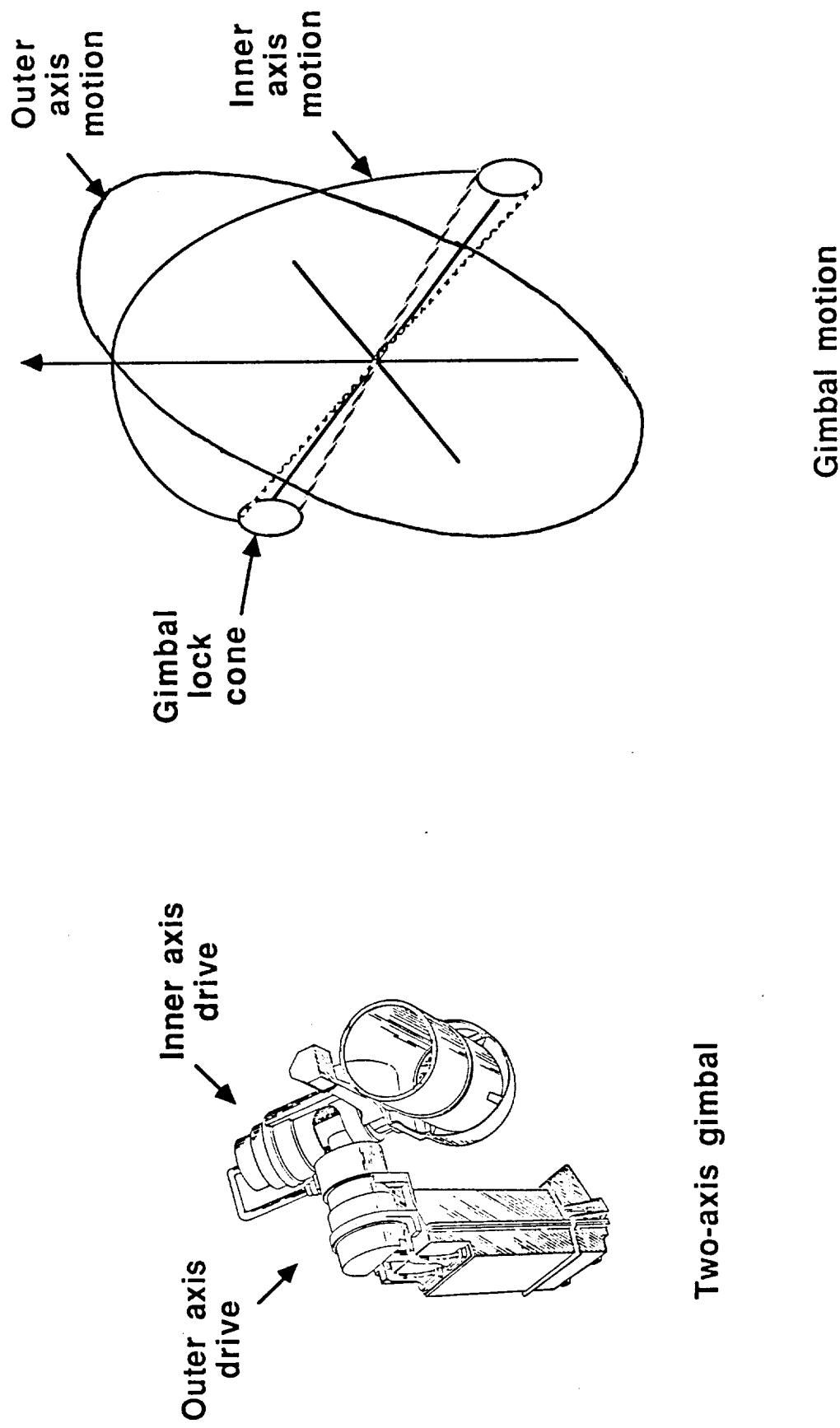
Two-axis gimbal

THREE-AXIS GIMBAL WITH FULL-HEMISPHERICAL ANGULAR COVERAGE

Shown on this chart are side and front views of the selected three-axis gimbal, including its physical dimensions, and showing the Coude' optical path emerging from the bottom of the gimbal pedestal. Hemispherical coverage is provided by the third axis that can be viewed as a means by which to rotate the gimbal lock cone away from the desired coverage area. As shown on a later chart, the optical terminal focal plane assembly will be placed in a rectangular support box upon which the gimbal is mounted. Finally, the dimensions shown apply to the 10-cm system. The 1-cm system, although not scaling down directly, because of the motor drives required for angular coverage, will be smaller than these dimensions by a factor of about the ratio of their respective weights (i.e., their densities are assumed identical).

SIDE AND FRONT VIEWS OF THREE-AXIS GIMBAL WITH FULL-HEMISPHERICAL COVERAGE

14"

8.5"

Front view

6"

3"
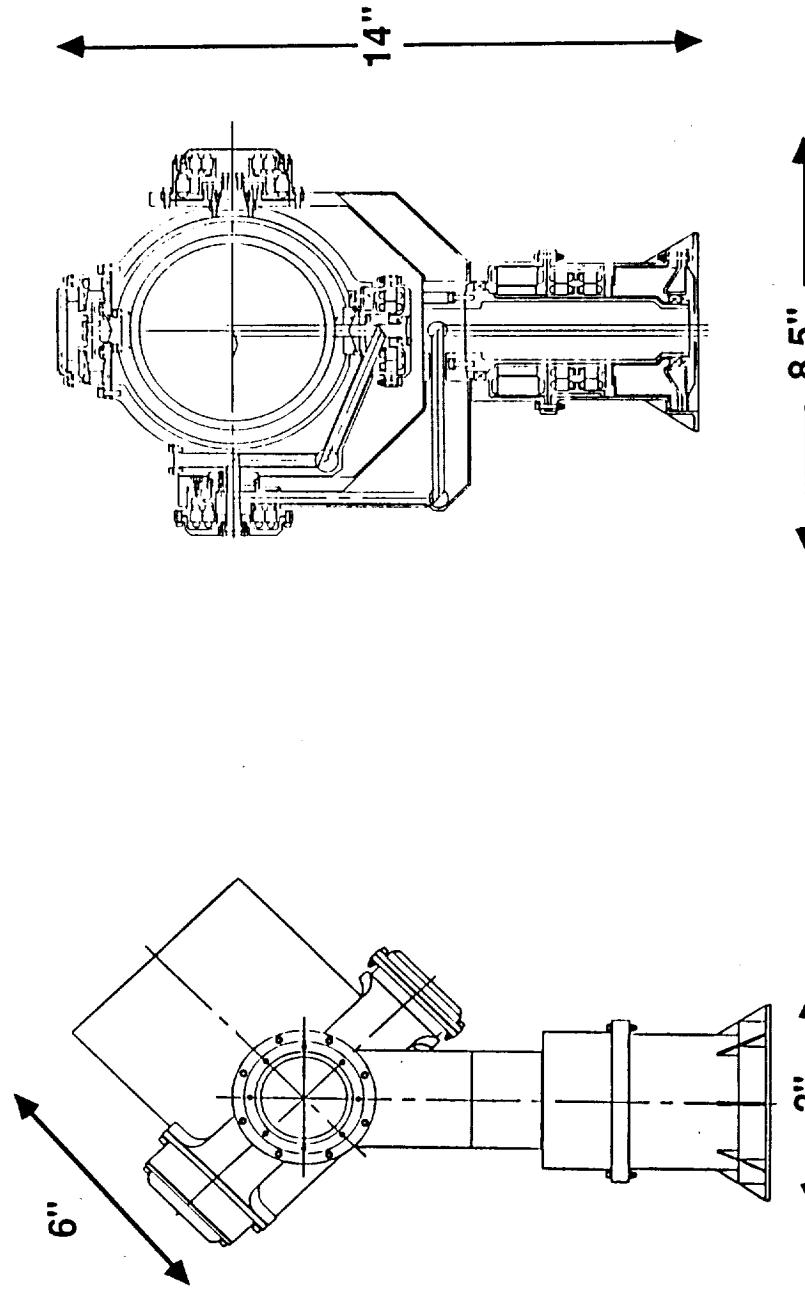
Side view

1-cm GIMBAL FEATURES

This chart summarizes the 1-cm gimbal design considerations, with an eye towards the desirable features of hemispherical coverage and low weight/complexity. A key element is the tradeoff between the gimballed-terminal and gimballed-telescope approaches. Detailed SWAP estimates in Section 5.0 indicate focal plane assembly requirements of 1250 cc, 3.3 lb and 12.6 W. Gimballing this size focal plane will require a larger gimbal weight than needed in the gimballed-telescope approach, making the latter approach preferable. The three-axis,1-cm gimballed telescope is estimated to weigh 2.5 kg. Note this weight is about 40-percent of that for the 10-cm system, thus supporting the approach for using a reduced aperture on the vehicle with its resulting less-efficient link budget.

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1-cm GIMBAL FEATURES

- Two configurations were considered:

  (1) Attach focal plane to the telescope
      and gimbal the entire optical terminal

      – Advantage: No light pathing through the gimbal
                   configuration

      – Disadvantage: Added gimbal weight due to
                      increased payload weight & size

  (2) Focal plane outside the gimbal. Same configuration
      as 10-cm optical terminal

      – Advantage: lighter payload on gimbal
      – Disadvantage: Coude' pathing through gimbal

- Conclusions

  – Weight considerations favor gimballed refractive telescope
    w/ Coude' optical path
  – Three-axis, 1-cm gimballed telescope weight estimated at 2.5 kg

189

NESTED-SERVO POINTING AND TRACKING CONCEPT

This chart diagrams the traditional nested-servo pointing and tracking control concept, whereby two pointing loops act jointly to provide accurate spatial tracking over a large angular field of regard (i.e., a large angular dynamic range). This concept is baselined for all but the FTS and MSC Prox-Ops links. The outer loop involves the gimbal and fine-pointing-mirror position sensors, and provides a hemispherical coverage while striving to keep the receive optical beam within the limited range of travel of the fine pointing mirror. The inner pointing loop consists of the quadrant track detector and fine pointing mirror, and provides accurate spatial tracking and platform disturbance rejection that allows efficient use of limited transmitter power to prevent the occurrence of burst errors that interrupt reliable communications. The gimbal/position sensor loop thus rejects large-amplitude, low-frequency platform disturbances, and the track-detector/fine-pointing mirror loop rejects low-amplitude, high-frequency platform disturbances. The alternative to this approach involves performing the fine and coarse pointing with the gimballed telescope, thus eliminating the need for the fine-pointing mirror. The issues associated with this alternative are discussed on the next chart.

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NESTED-SERVO POINTING AND TRACKING CONCEPT
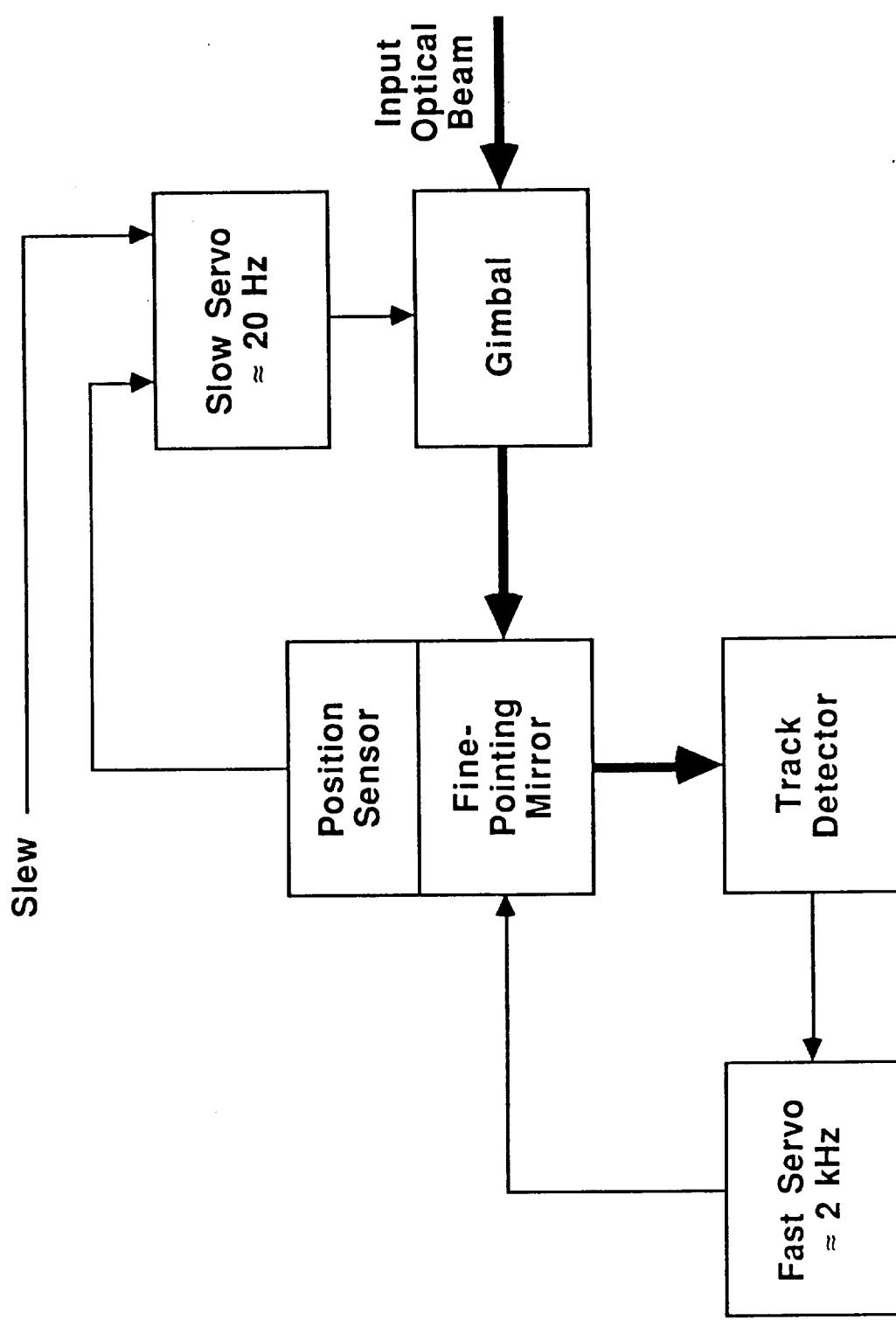
SPATIAL TRACKING USING GIMBALLED TELESCOPE

This chart assesses the issues involved with a potential simplification in Prox-Ops that results from the broad optical beams required to close the comparatively low-data-rate, short-range links. Summarizing, the gimbal tracking concept eliminates the need for a fine-pointing mirror, thereby reducing payload impact, but at the consequence of reduced performance in one key area: platform disturbance rejection. Consequently, even though this concept can theoretically provide the necessary pointing accuracy in the Prox-Ops links, its use is precluded in all but possibly the FTS and MSC terminals. This assumes that the dominant platform disturbances on the FTS and MSC are at low frequencies (a few Hz).

SPATIAL TRACKING USING GIMBALLED TELESCOPE

- In most cases, Prox-Ops uses relatively broad optical beams, thereby alleviating spatial tracking requirements

- Gimbal can be considered to provide "fine" tracking

  - Tracking provided by gimbal-angle-sensor/gimbal-drive loop with updates from track detector
    Eliminates need for FSM subsystem
  - Offers rms tracking accuracy on order 1 arcsec (5 μrad)
  - Consequently, could provide acceptable burst error rate performance for 100- to 125-μrad transmit beam
  - But offers very-limited disturbance-rejection bandwidth (gimbal bandwidth on order 20-50 Hz compared with 1700 Hz for FSM)
  - Not applicable to EVA/MMU because of its irregular platform disturbance spectrum
  - Applicability to FTS, MSC, SSF, and long-range vehicles dependent upon unknown platform disturbance spectra
  - First-cut assessments indicate the gimbal tracking approach may be applicable only to the FTS and MSC terminals

5.0 OPTICAL TERMINAL DESIGN

This section describes the design of the Prox-Ops optical terminals, beginning with discussions of subsystem issues, progressing to generic terminal layouts and size, weight, and prime power estimates, and concluding with detailed engineering drawings that indicate the terminal compactness.

194

5.0 OPTICAL TERMINAL DESIGN

- Operational modes

- Transmit/receive separation techniques

- Receiver dynamic range issues

- Generic terminal layout

- Size, weight, prime power estimates

- Engineering drawings

OPTICAL TERMINAL OPERATIONAL MODES

This flow diagram shows the various optical-terminal operating modes and indicates the interrelation between them. The terminal is placed in the SURVIVAL MODE whenever it is completely inactive for an extended period of time, during which a minimal amount of power is required to maintain the temperatures necessary for the precision optical, mechanical, and electronic subsystems. During the QUIESCENT MODE, the terminal microprocessor is active, accepting changes to operating software and monitoring health and status of operational subsystems. For applicable vehicles, periodic data transfers (e.g., TT&C) to/from ground sites can be performed. The STANDBY MODE prepares the system for full-up operations, whereby all lasers, detectors, and electronic circuits are brought to operating temperatures. The system is then prepared to quickly change to full operational mode upon receipt of the appropriate command. The system automatically returns to this mode should any acquisition/reacquisition sequence fail.

The first major operational mode is the ACQUISITION MODE, during which the two optical terminals to be linked proceed from open-loop pointing to closed-loop pointing and tracking compatible with communications. The Prox-Ops acquisition sequence has been described in detail earlier, but is summarized here for the sake of completeness. Prox-Ops acquisition is always initiated by SSF. In the first phase, SSF scans its 10-mrad FOU, and the vehicle receiver stares with a 20-mrad FOV and points a narrow beacon, compatible with fine tracking and communication, back to the estimated SSF location. For worst-case short-range acquisition, this step could be preceded by a coarse acquisition process involving a modulated SSF beacon and vehicle-based detector-cube sensor that provides the 20-mrad vehicle FOU. In either case, the vehicle uses multiple detections (8 to10 with PIN quad detector) of the receive SSF beacon to reduce its FOU, and ultimately point its narrow beacon directly at SSF. Threshold detection of the return vehicle beacon causes SSF to stop its scan, narrow its beacon, and scan the vehicle FOU once to perform FOU reduction that allows it to point the narrow beacon back to the vehicle. The quadrant detectors on each terminal are now ready to commence fine tracking and communication. If the terminals fail to acquire, the process is repeated based on revised position information. Repeated failure returns the system to the standby mode.

OPTICAL TERMINAL OPERATIONAL MODES
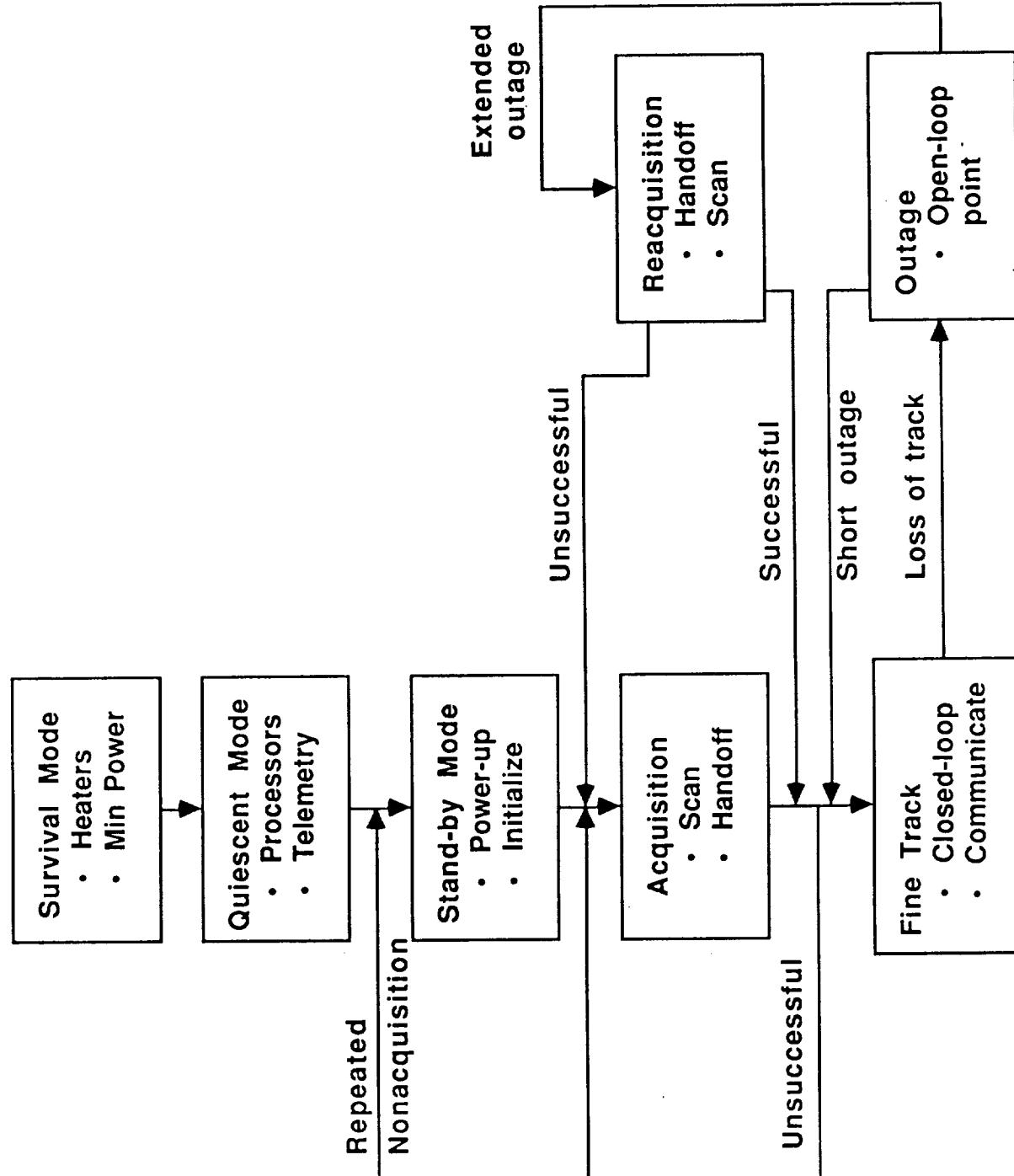
OPTICAL TERMINAL OPERATIONAL MODES (cont.)

With handover complete, the system proceeds to the FINE-TRACKING MODE, where the servo-control loop is closed around the PIN quadrant track detector to maintain pointing control compatible with reliable communications (i.e., adequate burst-error performance). After synchronization and initialization, the communications subsystem is in full-scale operations.

The track and communication signals are continually monitored to provide system status checks. A significant drop in the tracking SNR indicates a tracking loss, which switches the system to the OUTAGE MODE. Independent failures in communication performance are not considered outages, but do trigger on-board system checks. When the tracking signal falls below a preset minimum, the servo-control system switches to open-loop pointing, using data from the acquisition and tracking microprocessor. For short outages, the tracking signal quickly reappears and the system reverts to the fine-tracking mode.

Longer outages and repeated short outages shift the system to the REACQUISITION MODE. Examples of such outages in Prox Ops include solar conjunction (predictable) and link loss between EVA/MMU and SSF (unpredictable). For predictable outages, the system switches to open-loop pointing just before the outage, and proceeds to acquisition beacon scanning (on SSF) and FOU reduction (on the vehicle) following the outage, preceded by the modulated SSF beacon/detector-cube sensor sequence, as appropriate. For unpredictable outages, the system first attempts to restablish track by implementing a subset of the acquisition procedure, e.g., just before the the beginning of handoff. If that fails to restore tracking, a small search is implemented. If that fails, the system reverts to the acquisition mode, including the modulated SSF beacon/detector-cube sensor sequence, as appropriate.

199

TRANSMIT/RECEIVE SEPARATION TECHNIQUES

This chart summarizes the two transmit/receive options considered for Prox Ops, indicating their key advantages and disadvantages. The essential factor concerns the large number of Prox-Ops users; baselined at four and expected to grow in future phases. Although a wide range of emission wavelengths are selectable in the GaAlAs diode laser system, a large user count implies a narrow wavelength spacing for a dichroic system. Such a narrow spacing results in increased interference between users, owing to difficulties in wavelength discrimination with dielectric optical interference filters. The polarization technique effectively halves the number of wavelengths required to support a given user count, but presents operational difficulties with regards to transmit/receive isolation. The problem is not as demanding in Prox-Ops as in other optical systems, but adequate isolation is still required between the 50-mW transmitter power and the 1- to 50-nW receive optical signal. Inadequate isolation increases the receiver noise, thus hampering the communication and tracking subsystem performance. The key element in the decision is that four Prox-Ops users can be supported with the dichroic approach and a 10-nm wavelength spacing. This is not considered prohibitable to the system design, and affords adequate transmit/receive isolation. Growth in the user count would require revaluation of this decision.

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PRELIMINARY TERMINAL DESIGNS - TRANSMIT/RECEIVE SEPARATION TECHNIQUES

- Dichroic transmit/receive separation

  - Adequate T/R isolation readily achieved
  - Large wavelength count to access four simultaneous Prox-Ops users
  - Narrow wavelength spacing with larger user count could lead to inter-user interference, thereby defeating a main reason for an optical Prox-Ops

- Polarization transmit/receive separation

  - Adequate isolation difficult to achieve
  - Fewer wavelengths than dichroic method
  - Wavelengths assignable to vehicles

- Conclusion

  - Dichroic T/R method selected
  - Wavelength count achieved with 10-nm spacing (4 users)

PROX-OPS RECEIVER DYNAMIC RANGE

An additional characteristic that distinguishes the Prox-ops mission from many other laser communication systems is the large variation in link range. As a result, some form of receive optical power control is necessary to ensure adequate SNR from an optical receiver with limited dynamic range. As discussed earlier, a transimpedance receiver front-end has been baselined that sacrifices sensitivity for improved dynamic range, but even this is inadequate to support the large Prox-Ops range variations. As shown, three alternatives were considered for AGC of the receive optical power, and the variable attenuator approach was selected because of its simplicity.

LIMITED RECEIVER DYNAMIC RANGE IMPACTS PROX-OPS DESIGN

- Prox-Ops range variations are large

  - $0 < R < 37$ km, initial phase
  - $0 < R < 2000$ km, growth phase

- Limited receiver dynamic range implies need for AGC of received signal power

- AGC can be provided by

  - Focusing the transmit beam
  - Varying the transmitter laser drive current
  - Placing a variable attenuator in the receive path

- Conclusion: Variable attenuator is the least complex and preferred approach

  - Avoids need for "order wire"
  - AGC completed by single terminal

DIODE LASER TRANSMITTER ASSEMBLY

The chart shows the specific blocks comprising the laser transmitter, including a redundant source for reliability enhancement. Each laser is stabilized in temperature and optical power to compensate for variations in threshold current with temperature and time. Temperature tuning can also be used for fine adjustments in emission wavelength that could be useful with the narrow wavelength spacing in Prox Ops. Temperature stabilization to within about ± 0.1 °C is achieved using a Peltier (thermoelectric) cooler mounted flush against the diode that is part of a control loop containing a thermistor sensor. Optical power stabilization to within about ± 0.1 mW is achieved using an internal photodiode to monitor the rear laser facet, with feedback to control the laser drive current and maintain a constant average output power. Finally, electronic circuitry is required for matching the diode laser RF impedance to the modulation driver electronics (a 50-Ω line impedance is typical).

The modulation driver assumes the binary pulse position modulation format (BPPM), whereby a digital "0" sets the diode drive current to provide a $2P/(1 + r)$ peak power in the first half time slot and $2rP/(1 + r)$ in the second half time slot, with average source power P and extinction ratio r. Transmission of a digital "1" reverses the two half-slot peak powers.

The modulated optical beam is shaped using collimating and anamorphic optics. The collimating optics efficiently collect and collimate the widely divergent diode laser energy, and the anamorphic prism pair circularizes the elliptical angular divergence of the diode source output.

Finally, the redundancy feature is efficiently and reliably provided by a device that mechanically switches a glass block out of the optical path of the standby source. Such mechanical switches have been well-developed for application in undersea fiber-optic systems.

204

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DIODE LASER TRANSMITTER ASSEMBLY

205
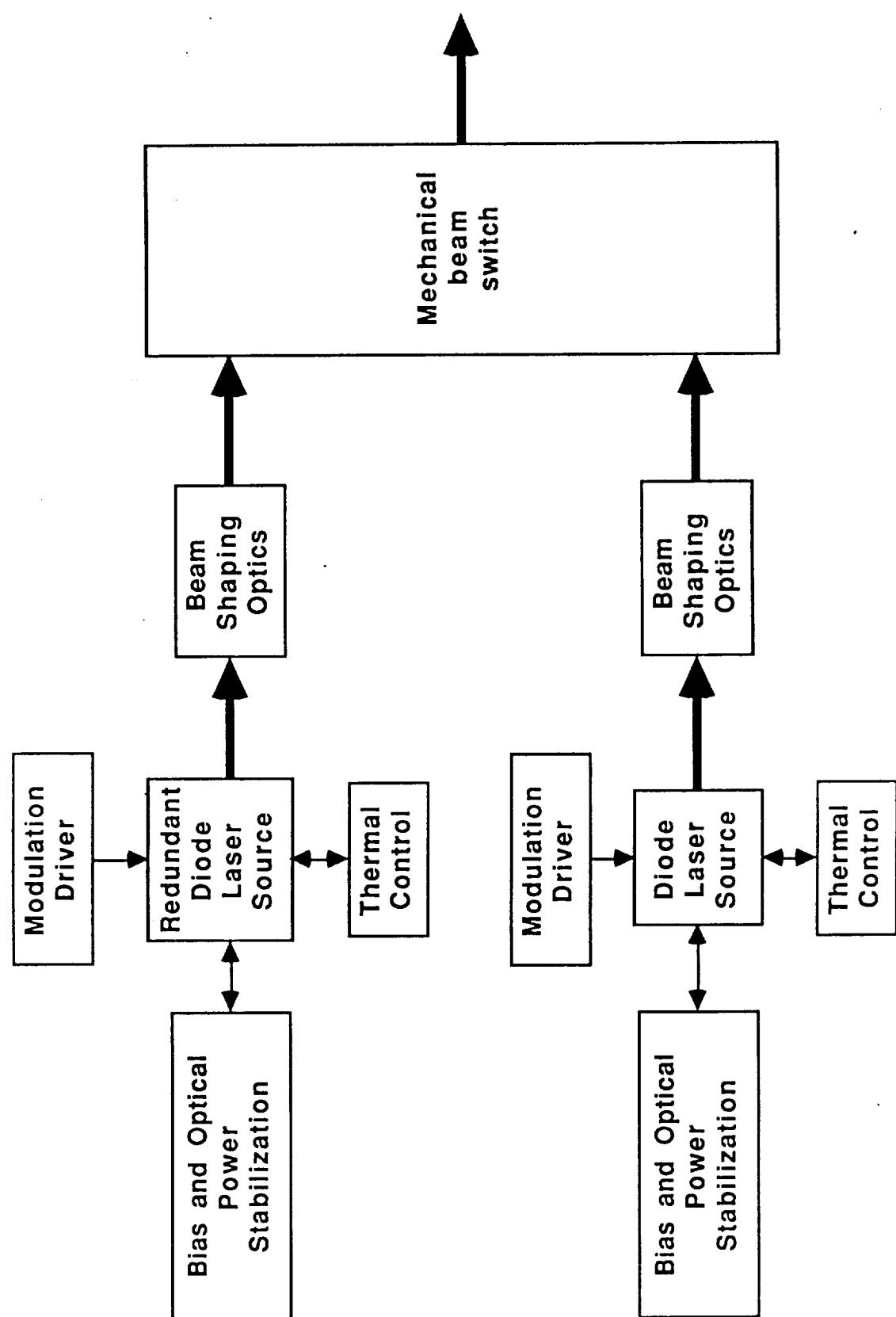
QUADRANT DETECTOR RECEIVER ASSEMBLY

The chart shows the specific blocks comprising the quadrant receiver that supports Prox-Ops acquisition, tracking, and communication.

Summarizing, the acquisition and communication electronics process the summed output of the four detector quadrants, ultimately using some form of threshold detection for receive signal interpretation. The tracking electronics, on the other hand, uses appropriate sum and difference signals to generate azimuth and elevation pointing errors that are sent to fine-pointing mirror to update the terminal boresight.

Demodulation of the preamplified and equalized BPPM communications signal involves comparing the signal energy in each of the two half time slots and selecting the largest value; a digital "0" is interpreted when the first half-slot dominates, a digital "1" if the second half-slot dominates. The clock-recovery circuit contains a transition detector (e.g., a differentiator followed by a rectifier) and a phase-locked loop or surface-acoustic-wave filter that extracts the timing signal. The clock signal is used to regenerate the demodulated receive data.

QUADRANT DETECTOR RECEIVER ASSEMBLY
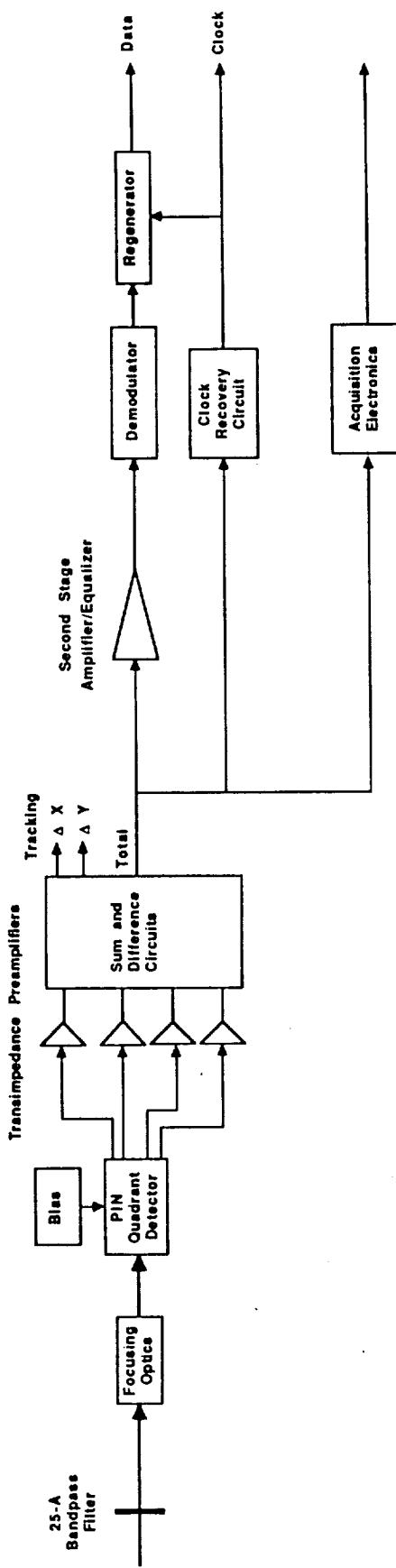
GENERIC FOCAL PLANE ASSEMBLY

This chart shows a block diagram of the generic Prox-Ops focal plane assembly (FPA), indicating a inherent simplicity that results from the selected design approach. Specifically, the FPA requires only a single laser assembly and a single PIN-quadrant-detector assembly to support acquisition, fine-tracking, and communication. This diagram is modified, as appropriate, in Section 6.0 to specifically define the optical terminals for the various Prox-Ops vehicles.

The variable focus collimator does not have to be continuously variable. Instead, a simple mechanical switch is sufficient that injects a glass block/lens into the optical path to change the transmit beam divergence between the ACQ and track/COMM states.

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GENERIC PROX-OPS FOCAL PLANE ASSEMBLY
USES DICHROIC TRANSMIT/RECEIVE SEPARATION
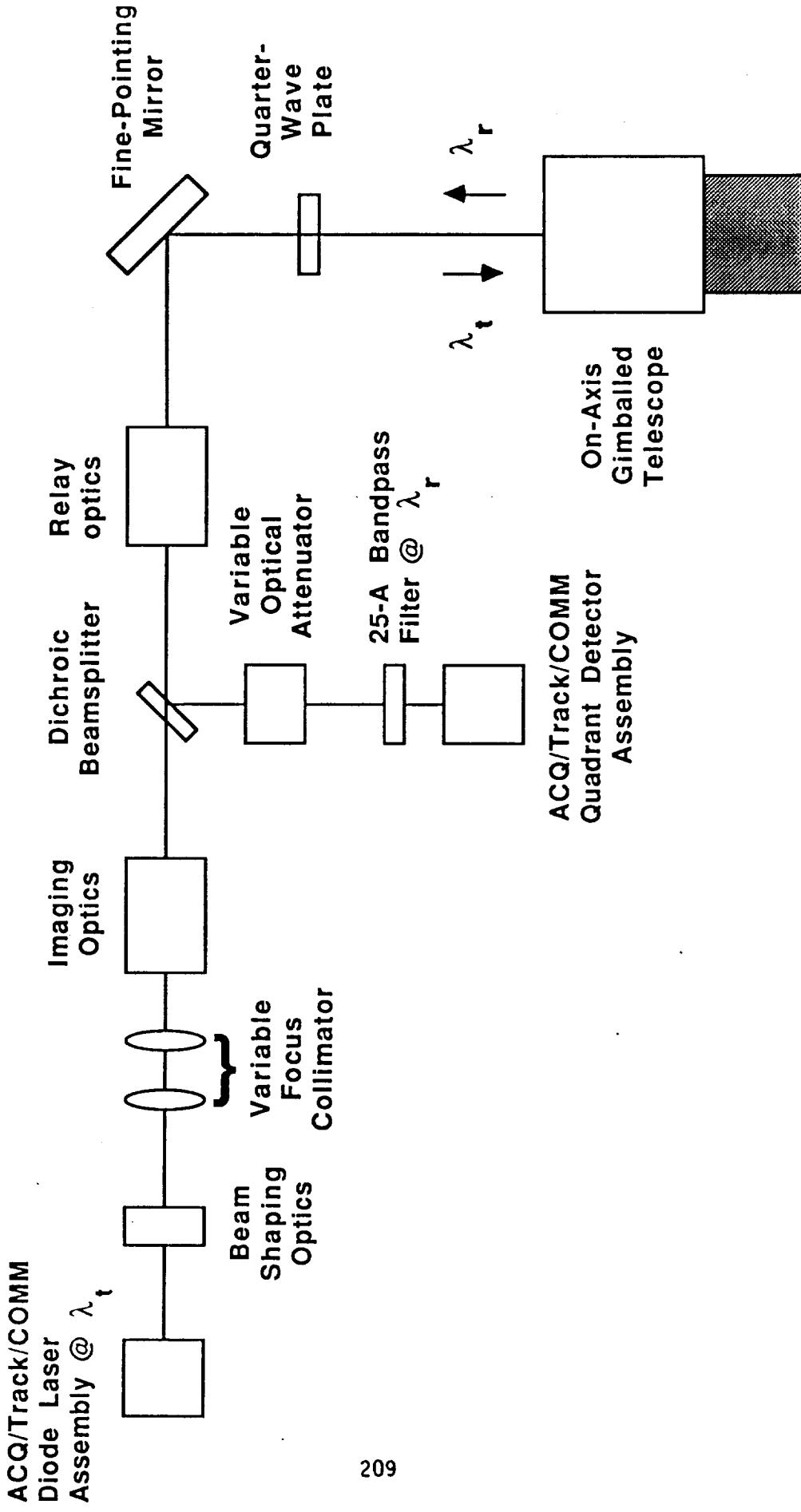
PRELIMINARY TERMINAL LAYOUT

This chart shows a preliminary mechanical layout of the optical components indicated on the previous block diagram. Note that the three-axis gimbal is mounted on top of the FPA which acts as a support base. Further, note that the focal plane size has been greatly expanded in this preliminary layout for the sake of clarity. More-detailed drawings indicating terminal compactness are provided on a later chart.

PRELIMINARY TERMINAL LAYOUT
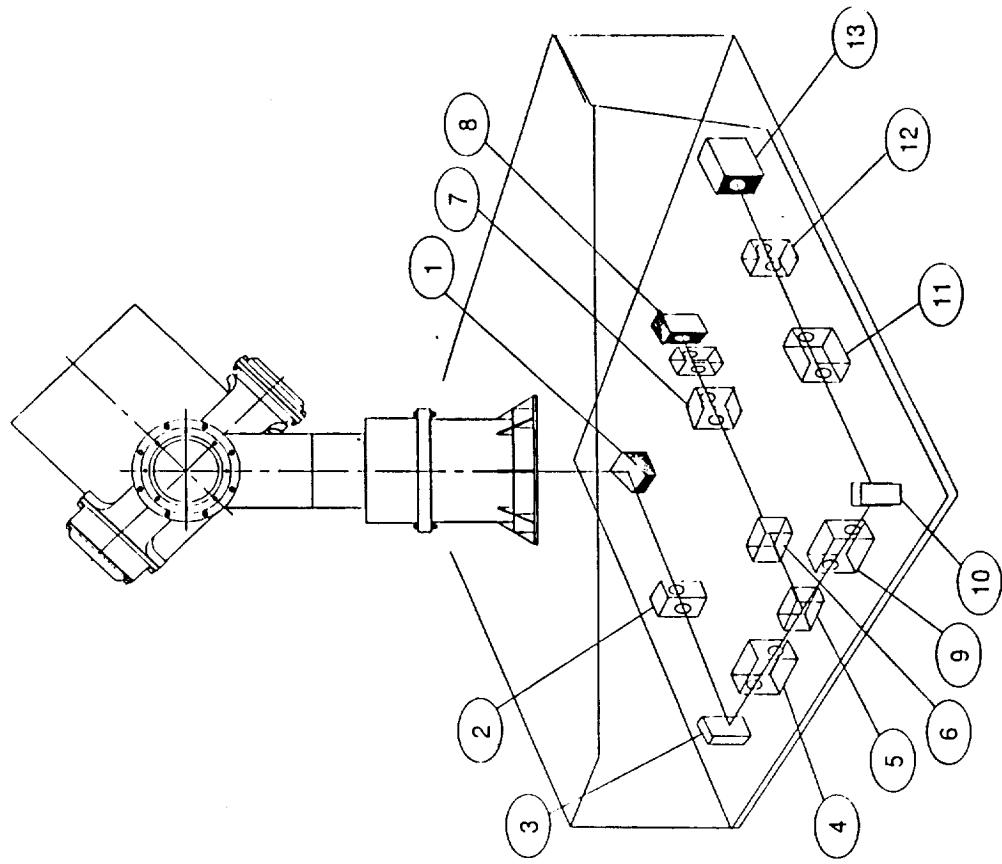
1. Fold mirror
2. Quarter-wave plate
3. Fine-pointing mirror
4. Relay optics
5. Dichroic beamsplitter
6. Variable optical attenuator
7. Background rejection filter
8. ACQ/Track/COMM detector and receiver module
9. Imaging optics
10. Fold mirror
11. Beam defocus assembly
12. Beam shaping optics
13. ACQ/Track/COMM diode laser transmitter module

** Focal plane dimensions are expanded for clarity

PRELIMINARY TERMINAL LAYOUT (cont.)

In addition to the optical and mechanical components shown on the previous charts, the optical terminal requires several support functions that allow proper operation of the various subsystems. The items listed on this chart become part of the terminal SWAP estimates to follow.

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PRELIMINARY TERMINAL LAYOUT (cont.)

- Optical terminal also requires support functions

  - Power conditioning electronics
  - Servo electronics
  - Commands and telemetry
  - Microprocessors
  - Signal conditioning electronics
  - Support structure and spacecraft interface
  - Thermal control

SIZE, WEIGHT, AND POWER ESTIMATES

The next several charts provide SWAP estimates for the generic Prox-Ops terminal shown on earlier charts. Detailed estimates are provided for the 10-cm system, and additional items are provided that allow the 1-cm estimates to be completed in the Section 6.0. This self-explanatory chart summarizes the basic methodology used for the estimates that follow. These engineering estimates are based on actual hardware data as far as possible, and standard electronic integration techniques are assumed to reduce the subsystem SWAP.

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SIZE, WEIGHT, AND POWER ESTIMATES

- SWAP estimating methodology

  - Engineering estimates based on realizable hardware
  - VLSI assumed for electronics
  - Weight estimates for each entry accurate to within about 0.2 kg
  - Size estimates accurate to within about 50 - 100 cc
  - Power estimates accurate to within about 0.5 W

215

10-cm TERMINAL SIZE, WEIGHT, AND POWER ESTIMATES

The next several charts provide specific SWAP estimates for a 10-cm Prox-Ops terminal based on the approach described on the previous chart.

ITEM	VOLUME (cm^3)	MASS (kg)	POWER (W)
ACQ/TRACK/COMM LASER 50-mW device Thermoelectric cooler & heat sink Rear-facet photodiode monitor Beam shaping optics Modulation and stabilization electronics Redundant laser assembly and optomechanical switch	400	0.5	2
VARIABLE FOCUS COLLIMATOR	100	0.1	0.1
IMAGING OPTICS, POLARIZING BEAMSPLITTER, RELAY OPTICS, QUARTER-WAVE PLATE	50	0.1	--
ACQ/TRACK/COMM DETECTOR Bandpass filter Receiver electronics, including regenerator and clock-recovery	200	0.2	0.3
VARIABLE ATTENUATOR	100	0.1	0.2

10-cm TERMINAL SIZE, WEIGHT, AND POWER ESTIMATES (cont.)

This chart continues the specific SWAP estimates for the 10-cm Prox-Ops terminal.

10-cm TERMINAL SIZE, WEIGHT, & POWER ESTIMATES (cont.)

ITEM	VOLUME (cm^3)	MASS (kg)	POWER (W)
FINE POINTING SUBSYSTEM Reactionless steering mirror and drive circuitry Servo electronics	400	0.7	10
GIMBALLED TELESCOPE Three-axis design 10-cm aperture	3500	6.5	20
POWER CONDITIONING ELECTRONICS (75-% efficiency)	200	0.5	9.7
SUPPORT ELECTRONICS Microprocessors Signal conditioning Commands and telemetry	200	0.2	3

10-cm TERMINAL SIZE, WEIGHT, AND POWER ESTIMATES (cont.)

This chart concludes the specific SWAP estimates for the 10-cm Prox-Ops terminal. Note the 10-percent margin included to account for those items not specifically addressed in the table. Comparison of these results and those obtained in similar estimates for more-typical laser communications terminals indicate that the Prox-Ops low-data-rate and short-range requirements allow for a significant reduction in payload impact. The key reasons behind this are the resulting reduced laser power and aperture requirements, and the ability to combine the acquisition, tracking, and communication functions on a single detector, rather than requiring separate detectors for each function. These items also greatly reduce system complexity.

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10-cm TERMINAL SIZE, WEIGHT, & POWER ESTIMATES (cont.)

ITEM	VOLUME (cm^3)	MASS (kg)	POWER (W)
MISCELLANEOUS Support structure & interface Cables and connectors.	--	0.5	--
THERMAL CONTROL	--	0.5	3
SUBTOTAL	5150	9.9	48.3
10-PERCENT MARGIN	520	1.0	4.8
TOTAL	5670	10.9 (24 lbs)	53.1

ADDITIONAL SWAP ITEMS

This chart provides SWAP estimates for those system components needed to assess the payload impact for the various Prox-Ops terminals, that are not included in the tables shown on the three previous charts. CCD/CID array detectors have not been baselined in the designs provided in Section 6.0, but the analysis has indicated their necessity for a growth-phase Prox-Ops; this estimate is not used in this report and is therefore provided for completeness sake only. Further, if the recommended follow-on effort proves the CID array approach suitable for vehicle ACQ, track, and COMM, this entry can be used to refine the SWAP estimates provided here.

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ADDITIONAL SWAP ITEMS FOR PROX-OPS

- 2 detector cubes for EVA/MMU reacquisition

  250 cm^3 , 0.2 kg, 0.2 W

- CCD/ CID acquisition array (incl. flip mirror) for long-range vehicles or large FOU (if needed)

  1500 cm^3 , 2 kg, 7.5 W

- 1-cm gimballed telescope

  1350 cm^3 , 2.5 kg, 20 W

10-cm PROX-OPS OPTICAL TERMINAL

This chart shows a detailed optomechanical layout for the 10-cm optical terminal baselined for use on SSF, STS, OMV, and the co-orbiters. Note the compactness of the design that entails an estimated payload impact of 5750 cc, 11 kg, and 55 W. The terminals used on the various vehicles will differ only in their transmit and receive wavelengths.

Specific focal plane elements are identified as follows:

1   Fold Mirror

2   Quarter-Wave Plate

3   Fine-Pointing Mirror (incl. Drive & Servo)

4   Relay Optics

5   Dichroic Beamsplitter

6   Variable Attenuator

7   Bandpass Filter

8   ACQ/Track/COMM Quadrant Detector Assembly

9   Imaging Optics

10   Fold Mirror

11   Variable Focus Collimator

12   ACQ/Track/COMM Laser Assembly

13   Power Conditioning Electronics

14   Support Electronics

Various prime-power and signalling cables are also shown.

As on an earlier chart, the focal plane has been expanded for clarity. As a point of size reference, the gimballed telescope accounts for about 60-percent of the total optical terminal volume.

224
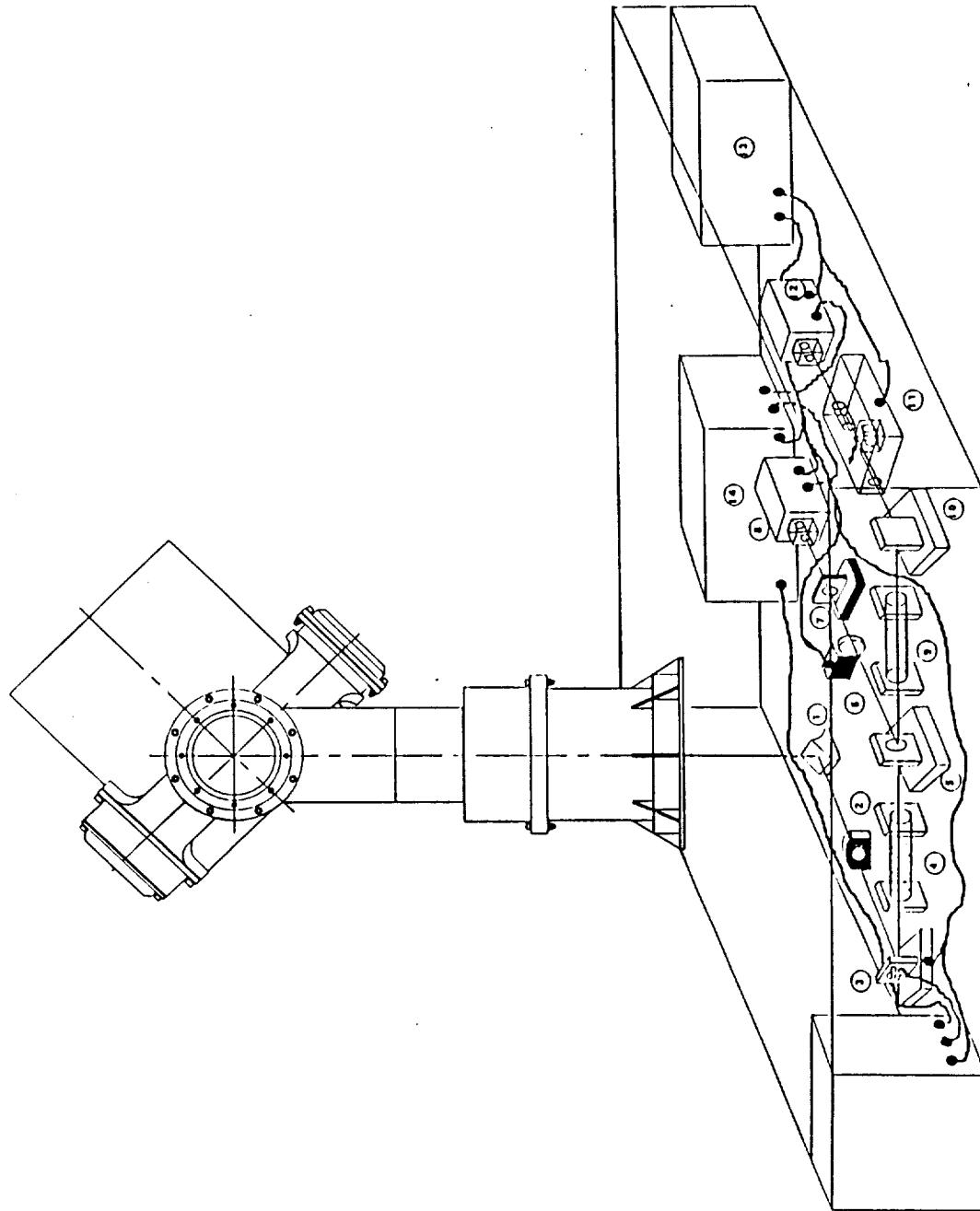
1-cm PROX-OPS OPTICAL TERMINAL

This chart shows a detailed optomechanical layout for the 1-cm optical terminal baselined for use on the EVA/MMU, FTS, and MSC. Again note the compactness of the design that entails an estimated payload impact of 4000 cc, 7.5 kg, and 55 W for the EVA/MMU, and 3000 cc, 6.5 kg, and 40 W for the FTS and MSC. Contrary to the 10-cm systems, the EVA/MMU and FTS/MSC terminals differ by much more than their transmit and receive wavelengths. Specifically, as discussed in Section 6.0, the EVA/MMU terminal provides a dual-wavelength transmit and receive capability to afford any two astronauts the ability to transmit and receive at distinct wavelength pairs. The FTS and MSC terminals are assumed to possess a less-stressing platform disturbance spectrum that is dominated by low-frequency fluctuations, allowing the fine tracking to be performed by the gimbal subsystem and removing the need for a FSM and its associated support electronics.

Specific focal plane elements are the same as those on the previous chart. The focal plane has again been expanded for clarity, and for this terminal, the gimballed telescope accounts for between 35- and 45-percent of the total volume. Note also that a pair of coarse-acquisition, detector-cube sensors have been included. The sensor mounting positions shown here are for illustration purposes only. Better mounting sites can likely be identified that minimize shadowing effects; for example, on the edges of the FPA support box.

1-cm PROX-OPS OPTICAL TERMINAL
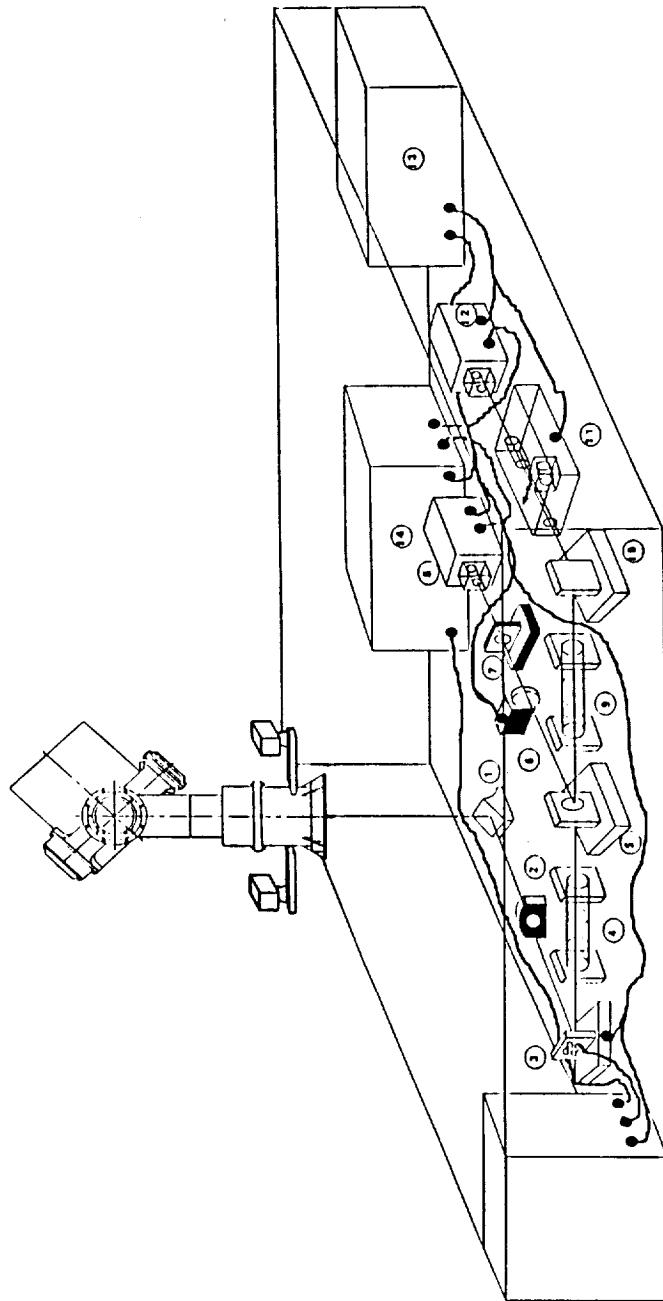
6.0 PROX-OPS SYSTEM DESIGN

This section describes the system-level Prox-Ops design, including the considerations for the long- and short-range vehicles and SSF. Issues addressed in the design include assignment of wavelength pairs to the various terminals, and discussions on coping with LOS obscurations. The section concludes with a progression of drawings that begin with the full SSF baseline configuration and expand in resolution to indicate the small payload impact of the 10-cm optical terminal.

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6.0 PROX-OPS SYSTEM DESIGN

- Long-range vehicle summary

- Short-range vehicle summary

- Wavelength management

- Line-of-sight obscurations and antenna handover

- Optical terminal placement on SSF

229

LONG-RANGE LINK SUMMARY

This chart summarizes the earlier performance analyses of the long-range Prox-Ops links. These results are used in the next several charts to design appropriate optical systems for SSF and the vehicles.

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SUMMARY OF LONG-RANGE LINK ANALYSES

- 50-mW GaAlAs diode laser, PIN quadrant detector, and 10-cm apertures can support acquisition, tracking, and communication between SSF and OMV, STS, co-orbiters

- Acquisition results

  - Initial phase (R = 37 km) uses modulated beacon, 10-mrad SSF FOV, and 20-mrad vehicle FOV
  - Growth phase (R = 2000 km) requires higher far-field power density, CCD array with CW beacon, or reduced initial FOU

- Fine tracking results

  - CW track beacon sufficient up to R = 37 km
  - At R = 2000 km, modulated track beacon required to combat Moon background in 20-mrad FOV

- Communication results

  - Growth phase becoming power limited with above selections (narrow transmit beam divergence)

- Solar outage will occur

  - Fine tracking can be maintained, but requires modulated beacon and separate quadrant detector with reduced (several hundred microradian) FOV

231

LONG-RANGE SPACE STATION TERMINAL

Shown are the characteristics required of the SSF-based terminal that supports bidirectional communication with the OMV, STS, or co-orbiters. As shown, the angular paths of these vehicles are well known, but two SSF terminals are required to support their approach to SSF from either the front or back. Once the appropriate hemisphere is established, virtually unobscured communication should be realized by mounting the SSF terminal on a mast that places it physically away from the space station structure and attached payloads, etc. If the long-range vehicle approaches from behind and desires to dock at the front of SSF, an antenna handover between the back and front SSF terminals will be required when the vehicle nears the front/back crossover plane. Finally, for this study, it is assumed that only one duplex long-range COMM link is operating at any given time. It is therefore prudent to reuse the same transmit/treceive wavelength pair for the three long-range vehicles. With this selection, the same front/back SSF terminal pair can be used for bidirectional COMM with the OMV, STS and co-orbiters.

LONG-RANGE SPACE STATION TERMINAL

- Operational scenario ⟶ At most one duplex long-range link at any time

  - Transmit @ 0.5 Mbps
  - Receive @ 25 Mbps

- 0 km < R < 37 km initial phase ⎫
  0 km < R < 2000 km growth phase ⎬ ⟶ Limited receiver dynamic range implies need for AGC of received signal level

- Main communication zone in plane parallel to Earth's surface

  - Two terminals (front and back coverage) provide nearly full-spherical angular coverage for approaching vehicle
  - Obscurations minimized (eliminated) by mounting on mast near center of Space Station

LONG-RANGE SSF FOCAL PLANE ASSEMBLY

This chart shows a block diagram of the SSF FPA that supports bidirectional communication with the OMV, STS, and co-orbiters at the specified transmit and receive wavelength pair.

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PROX-OPS SSF FOCAL PLANE ASSEMBLY (LONG RANGE)
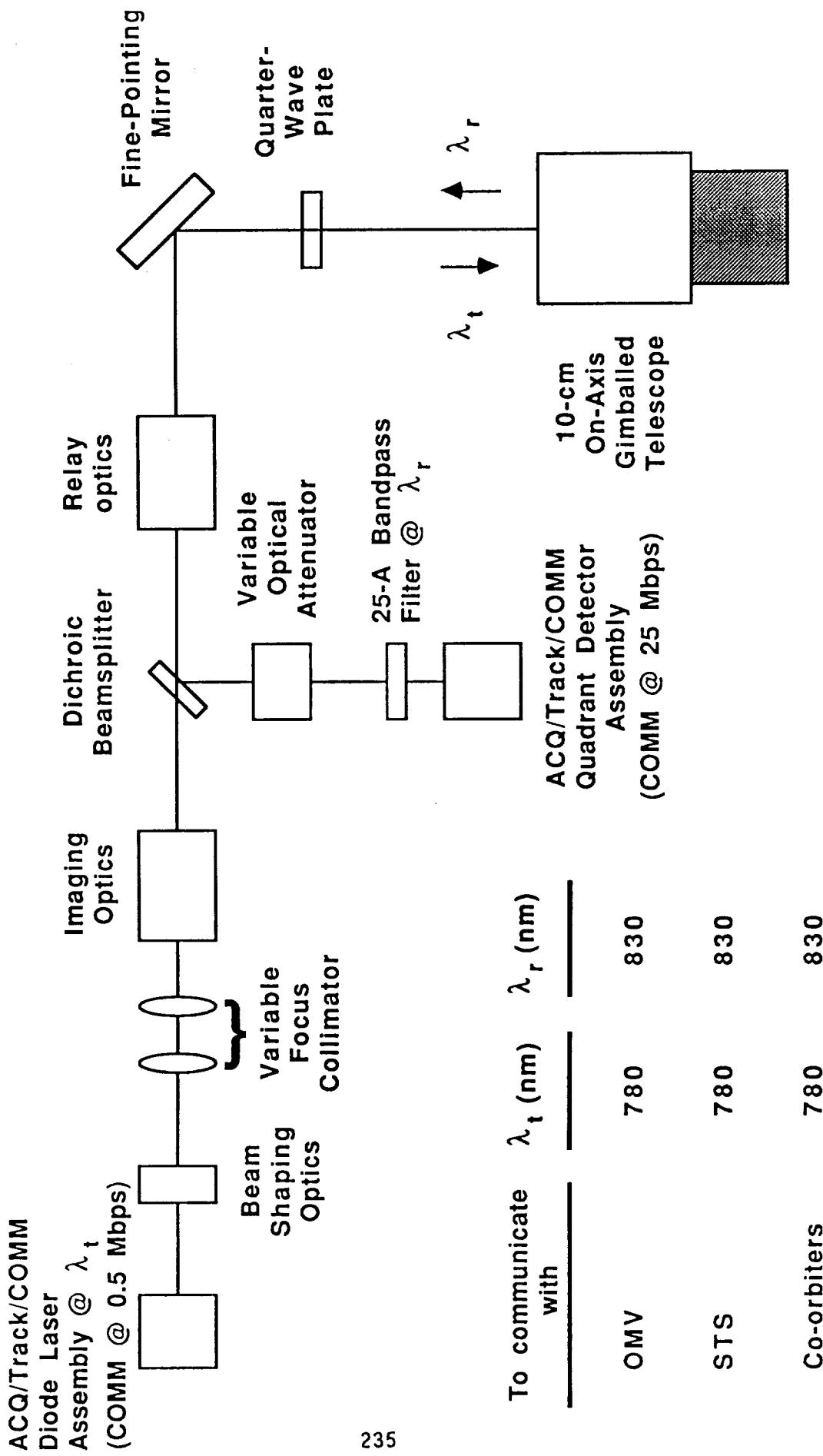
ACQ/Track/COMM
Diode Laser
Assembly @ λ_t
(COMM @ 0.5 Mbps)

Beam Shaping Optics

Variable Focus Collimator

Imaging Optics

Dichroic Beamsplitter

Relay optics

Fine-Pointing Mirror

Quarter-Wave Plate

λ_r

λ_t

10-cm On-Axis Gimballed Telescope

Variable Optical Attenuator

25-A Bandpass Filter @ λ_r

ACQ/Track/COMM Quadrant Detector Assembly
(COMM @ 25 Mbps)

To communicate with	λ_t (nm)	λ_r (nm)
OMV	780	830
STS	780	830
Co-orbiters	780	830

235

LONG-RANGE VEHICLE TERMINAL

Shown are the characteristics required of the vehicle-based terminal that supports bidirectional communication with SSF. The angular coverage requirements are not as demanding as for other Prox-Ops terminals. In fact, as discussed earlier, a two-axis gimbal might well be sufficient, with the only questionable area being when the vehicle crosses from the front to the back of SSF. For this reason and because of design commonality issues, a three-axis gimbal design is baselined. Vehicle interference is virtually eliminated by mounting the gimbal as close as possible to the vehicle end facing SSF. As described on the previous chart, the assumption that only one duplex long-range COMM link is operating at any given time makes it prudent to reuse the same transmit/treceive wavelength pair for the three long-range vehicles. This makes their optical terminals identical and is therefore favorable from a design commonality point of view.

LONG-RANGE VEHICLE TERMINAL

- Supports one duplex link

  - Transmit @ 25 Mbps
  - Receive @ 0.5 Mbps

- 0 km < R < 37 km initial phase
  0 km < R < 2000 km growth phase

  } ⟶ Limited receiver dynamic range implies need for AGC of received signal power

- Main communication zone in plane parallel to Earth's surface

  - Single terminal provides adequate coverage
  - Best mounted near vehicle end facing Space Station

237

LONG-RANGE VEHICLE FOCAL PLANE ASSEMBLY

This chart shows a block diagram of the vehicle FPA that supports bidirectional communication with SSF at the specified transmit and receive wavelength pair.

238

PROX-OPS LONG-RANGE VEHICLE FOCAL PLANE ASSEMBLY

Fine-Pointing
Mirror

Quarter-
Wave
Plate

λ_r

λ_t

10-cm
On-Axis
Gimballed
Telescope

Relay
optics

Variable
Optical
Attenuator

25-A Bandpass
Filter @ λ_r

ACQ/Track/COMM
Quadrant Detector
Assembly
(COMM @ 0.5 Mbps)

Dichroic
Beamsplitter

Imaging
Optics

Variable
Focus
Collimator

Beam
Shaping
Optics

ACQ/Track/COMM
Diode Laser
Assembly @ λ_t
(COMM @ 25 Mbps)

Vehicle	λ_t (nm)	λ_r (nm)
OMV	830	780
STS	830	780
Co-orbiters	830	780

239
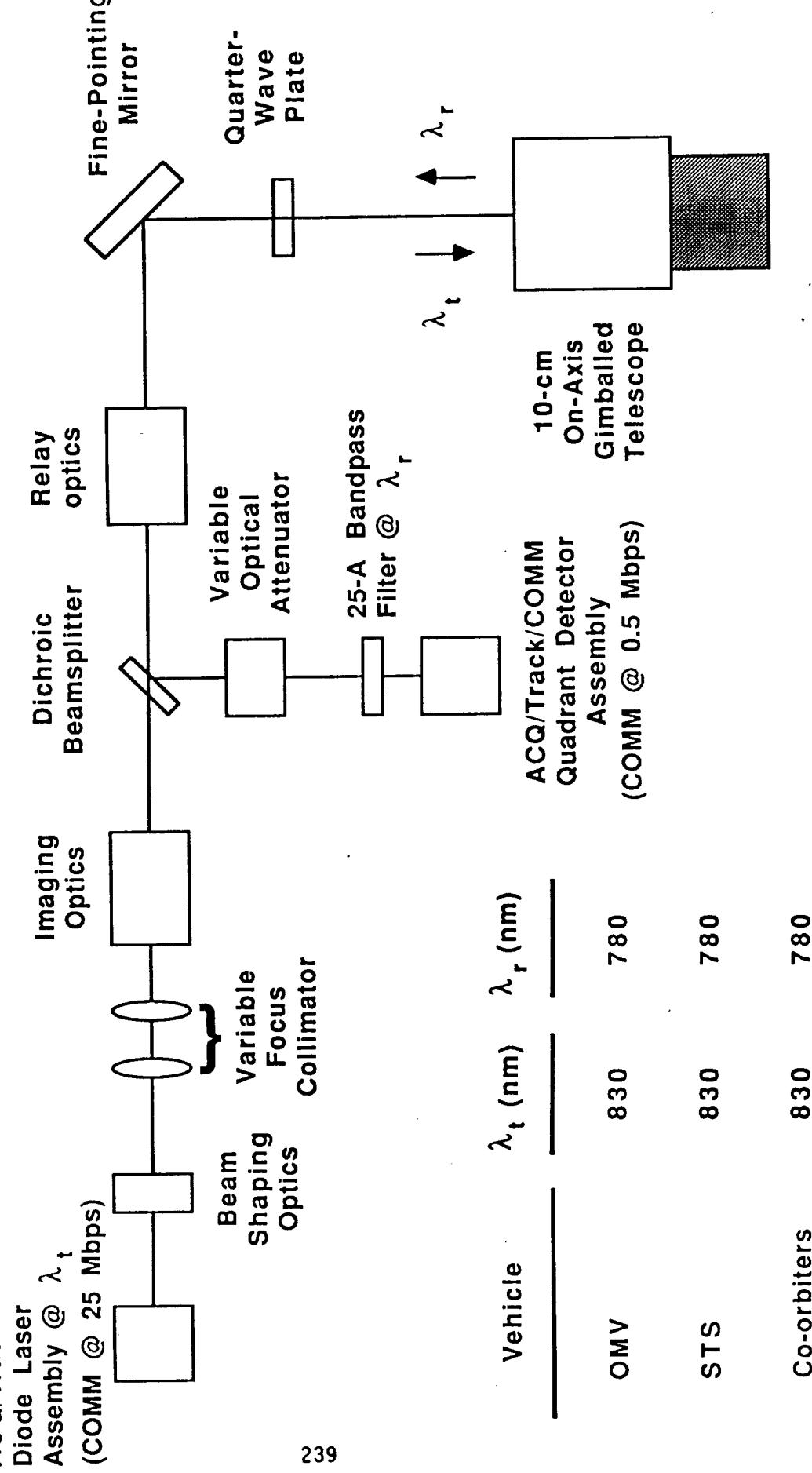
SHORT-RANGE LINK SUMMARY

This chart summarizes the earlier performance analyses of the short-range Prox-Ops links. These results are used in the next several charts to design appropriate optical systems for SSF and the vehicles.

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SUMMARY OF SHORT-RANGE LINK ANALYSES

- 50-mW GaAlAs diode laser, PIN quadrant detector, 1-cm aperture (vehicle), and 10-cm aperture (Space Station) support acquisition, tracking, and communication to EVA/MMU, FTS, and MSC

- Solar outage will occur

  - Fine tracking can be maintained, but requires modulated beacon and separate quadrant detector with reduced (several hundred microradian) FOV

SHORT-RANGE SPACE STATION TERMINAL

The next two charts show the characteristics required of the SSF-based terminals supporting up to four simultaneous bidirectional communication links with the EVA/MMU, FTS, and MSC. The EVA/MMU are assumed to always go out in pairs, and this activity will never be simultaneous with communications to the STS or co-orbiters. Simultaneous SSF communications between the EVA and the OMV are allowed.

A space-division-multiplex access scheme has been selected to accommodate the four simultaneous links, involving a separate terminal on SSF for each bidirectional link. This selection is based on the extreme difficulty in establishing a multiple-access system over large relative angles with a single optical terminal. Furthermore, the Prox-Ops optical terminals have been shown to entail a small payload impact, so that multiplicity should be of only minor concern on SSF.

Another tradeoff considered is between: (1) Multiple SSF terminals individually designed for each of the bidirectional vehicle links and (2) A single SSF terminal design that accommodates bidirectional COMM with all vehicles, but using only one transmit/receive wavelength pair at any time. The first approach is simplest by dedicating one wavelength to each SSF-based terminal, but could potentially require a large terminal count to support spherical coverage to four vehicles around SSF. The second design approach provides the SSF terminals with a four-wavelength-pair communication capability, but a close look at the Prox-Ops mission indicates that hemispherical coverage is needed only to support the EVA activity. The FTS, MSC, and approaching or exiting long-range-vehicle angular positions are relatively well-known, so that much less than a full-spherical coverage is required for their support.

The EVA mission demands a full-spherical coverage, requiring a multiplicity of terminals to support communication despite obscurations. When near SSF, obscurations will be prevalent and the COMM requirements are best supported in this author's view by a tethered link. When EVA is away from SSF, a free-space solution is viable, and can be supported by two three-axis gimbals that provide front and back coverage. As discussed on a later chart, each EVA is assigned two distinct wavelength pairs to allow any two astronauts to operate at distinct transmit/receive wavelengths. The SSF terminals that support the EVA activity can be designed to accommodate either one or both wavelength pairs. Since the SSF terminals provide hemispherical (front or back) coverage, each can be assigned a single wavelength and support the mission; this is the simplest and preferred approach. At least two terminal pairs (one pair each for front and back coverage, front or back pair COMMs with the two EVAs) are required to support EVA activity.

SHORT-RANGE SPACE STATION TERMINAL

- Operational scenario → Up to four duplex short-range links at any one time

  - Each transmits @ 0.5 Mbps
  - Each receives @ 25 Mbps

- Space-division-multiplex access scheme selected

  - Separate terminal on Space Station for each link
  - Interference minimized by assigning wavelength pairs to vehicles
  - Simplest and favored implementation: Space Station terminals each receive one wavelength
  - More versatile (yet complicated) implementation: Space Station terminals accommodate four separate wavelength pairs with grating multiplexer and demultiplexer;
    Advantages - Built-in redundancy, Design commonality
    Disadvantages - Higher complexity and weight, Added complexity needed only to support EVA/MMU pair

- EVA/MMU link availability increased by establishing two duplex links

  - Same wavelengths, separate terminals
  - Terminal mounting sites selected to minimize (avoid) mutual obscurations and interference

243

SHORT-RANGE SPACE STATION TERMINAL (cont.)

If allowed by the limited EVA/MMU weight budget, it is desirable to incorporate two vehicle terminals that allow establishment of two duplex links and thereby minimize the possibility of total link outage. Although the challenging reacquisition requirements that emerge from a total outage have been shown solvable by the coarse-acquisition detector-cube sensor, this situation entails changes in the system operating modes, etc. that increases complexity, and is simply a situation to be avoided as often as possible.

As in the long-range design, obscurations to the short-range vehicles are essentially eliminated by mounting the optical terminals on a mast to reduce potential LOS blockage by the SSF structure and attached payloads. The FTS and MSC terminals are best mounted at the two ends of the MSC track, with an additional terminal in the middle possibly being useful. As discussed above, the two EVA/MMU links are supportable when the EVA is away from SSF, by using two terminals for each EVA to provide the necessary front and back coverage. Antenna handovers are required between the front- and back-coverage terminals whenever the EVA nears the front/back crossover plane.

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SHORT-RANGE SPACE STATION TERMINAL (cont.)

- Two terminals (front and back) provide nearly full-spherical coverage

  - Obscurations to vehicles when away from SSF minimized by mounting terminals on mast
  - Obscurations near SSF pose a formidable problem; Tethered approach probably best

- $0 < R < 1$ km $\longrightarrow$ Limited receiver dynamic range demands AGC of received signal power

SHORT-RANGE SSF FOCAL PLANE ASSEMBLY

This chart shows a block diagram of the SSF FPA that supports bidirectional communication with the EVA/MMU, FTS, and MSC at the specified transmit and receive wavelength pairs.

PROX-OPS SSF FOCAL PLANE ASSEMBLY (SHORT RANGE)
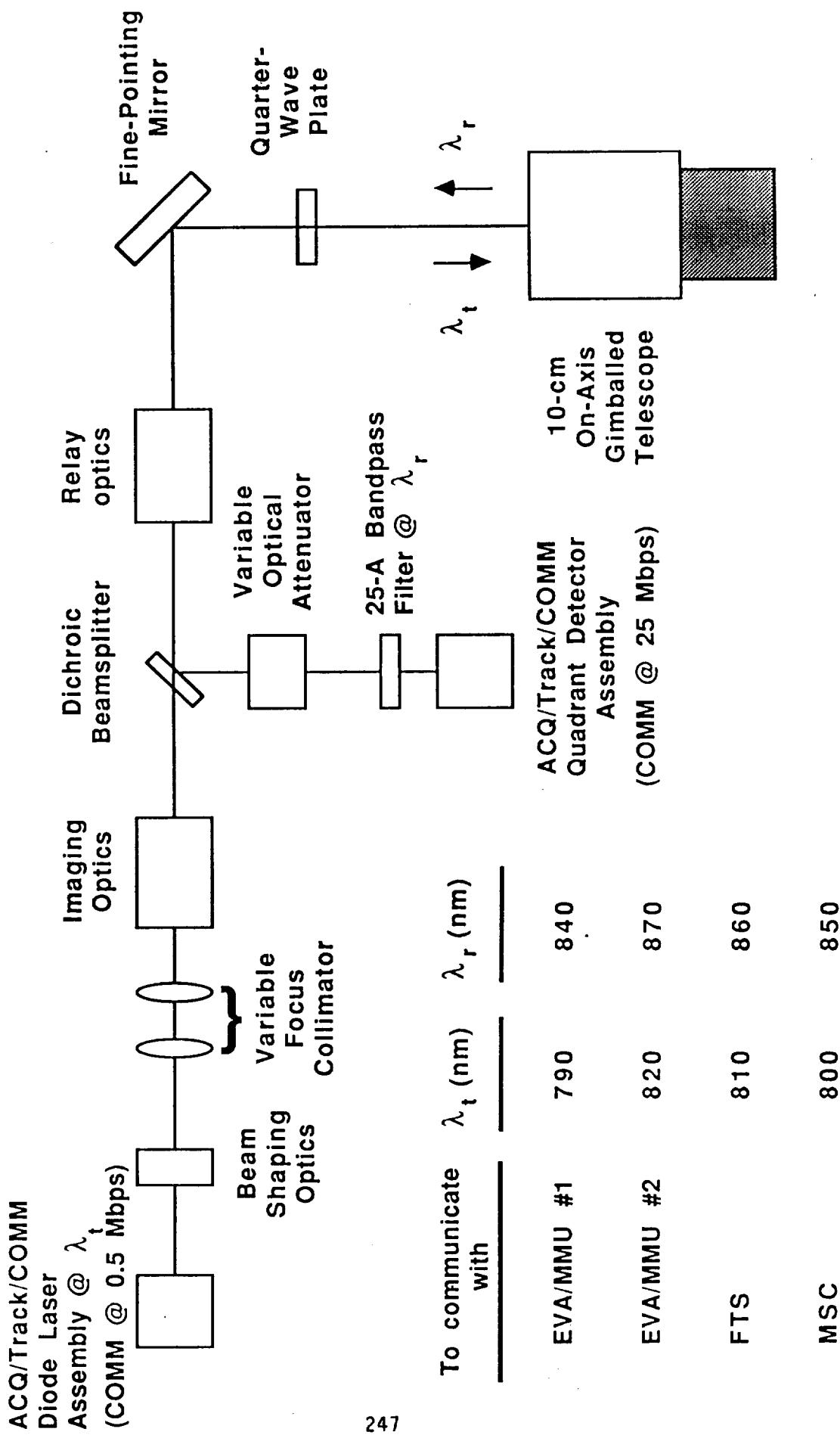
Fine-Pointing Mirror

Quarter-Wave Plate

λ_r

λ_t

10-cm On-Axis Gimballed Telescope

Relay optics

Dichroic Beamsplitter

Variable Optical Attenuator

25-A Bandpass Filter @ λ_r

ACQ/Track/COMM Quadrant Detector Assembly

(COMM @ 25 Mbps)

Imaging Optics

Variable Focus Collimator

Beam Shaping Optics

ACQ/Track/COMM Diode Laser Assembly @ λ_t

(COMM @ 0.5 Mbps)

To communicate with	λ_t (nm)	λ_r (nm)
EVA/MMU #1	790	840
EVA/MMU #2	820	870
FTS	810	860
MSC	800	850

SHORT-RANGE VEHICLE TERMINAL

Shown are the characteristics required of the vehicle-based terminal that supports bidirectional communication with SSF. The details summarized on this chart have been described on previous charts.

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SHORT-RANGE VEHICLE TERMINAL

- Supports one duplex link

  - Transmit @ 25 Mbps
  - Receive @ 0.5 Mbps

- Wavelength pairs assigned to vehicles

  - Vehicles entering from, exiting to, or remaining in the
    long-range zone use the long-range Prox-Ops terminal
  - If weight budget allows, EVA/MMUs are equipped
    with two terminals, each with two wavelength pairs
    -- Back-up link provision
    -- Each astronaut can transmit and
       receive at distinct wavelengths
  - MSC and FTS equipped with two additional wavelength pairs
  - Large wavelength count in Prox-Ops requires fairly narrow
    spacing; not an excessive requirement with four simultaneous
    users (could be an issue as number of users grows)

- $0 < R < 1$ km $\longrightarrow$ Limited receiver dynamic range demands
  AGC of receive signal power

249

SHORT-RANGE VEHICLE FOCAL PLANE ASSEMBLY

This chart shows a block diagram of the FTS and MSC FPAs that support bidirectional communication with SSF at the specified transmit and receive wavelength pairs. Note that the fine pointing mirror has been replaced by a fold mirror. As discussed earlier, fine and coarse pointing are both provided by the gimbal mechanism, based on the assumption that the platform disturbance for these two vehicles can be sufficiently rejected by the low-bandwidth quadrant-detector/gimbal/gimbal-angle-sensor control loop. Further investigation into the FTS/MSC platform disturbance spectra is warranted to establish the validity of this assumption.

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PROX-OPS SHORT-RANGE VEHICLE FOCAL PLANE ASSEMBLY

Fold Mirror

Quarter-Wave Plate

λ_r

λ_t

1-cm On-Axis Gimballed Refractive Telescope

Relay optics

Variable Optical Attenuator

25-A Bandpass Filter @ λ_r

Dichroic Beamsplitter

Imaging Optics

ACQ/Track/COMM Quadrant Detector Assembly (COMM @ 0.5 Mbps)

Variable Focus Collimator

Beam Shaping Optics

ACQ/Track/COMM Diode Laser Assembly @ λ_t (COMM @ 25 Mbps)

Vehicle	λ_t (nm)	λ_r (nm)
FTS	860	810
MSC	850	800

251
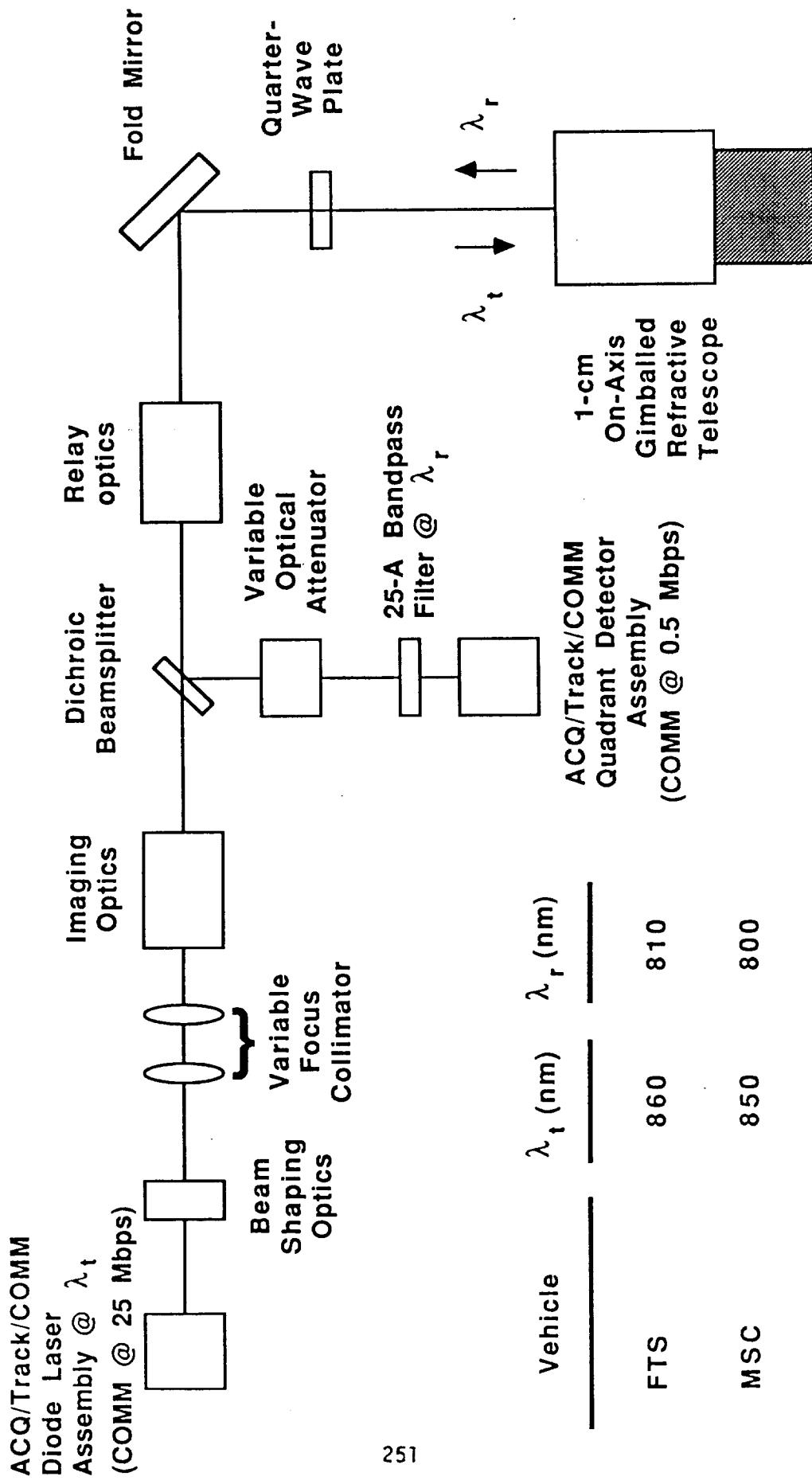
EVA/MMU FOCAL PLANE ASSEMBLY

This chart shows a block diagram of the EVA/MMU FPA that supports bidirectional communication with SSF, and allows any two astronauts to COMM at distinct transmit/receive wavelength pairs. Each astronaut can select either of the transmit wavelengths provided by the two laser assemblies that are combined by the dichroic element. Their transmit wavelength selection automatically selects the appropriate matched receive wavelength on the astronauts. The following transmit receive pairings are compatible with the SSF terminal design: (840 nm transmit, 790 nm receive) and (870 nm transmit, 820 nm receive).

EVA/MMU FOCAL PLANE ASSEMBLY ACCOMMODATES TWO TRANSMIT/RECEIVE WAVELENGTH PAIRS
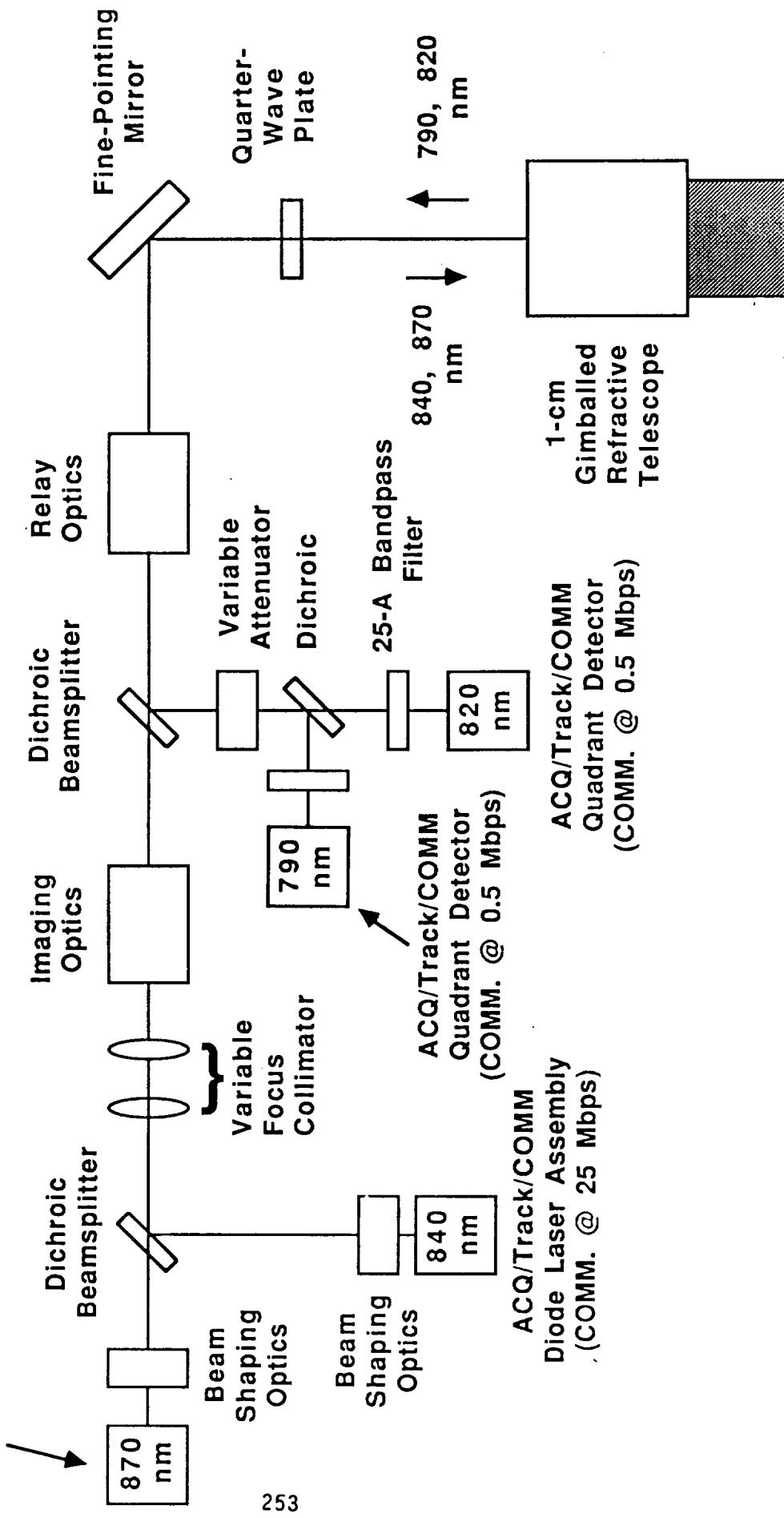
WAVELENGTH ALLOCATION SUMMARY

The next several charts summarize the Prox-Ops wavelength management. Shown on this chart are underlying assumptions for the system design that determine the wavelength count and resultant spacing between adjacent wavelengths. These assumptions are also important from the perspective of spectrum conservation, i.e., to provide the largest possible adjacent wavelength spacing and minimal inter-user interference.

254

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WAVELENGTH ALLOCATION SUMMARY

- Transmit/receive wavelength pairs are assigned to Prox-Ops vehicles

- At most one long-range link at any time

  – OMV, STS, and co-orbiters are never simultaneous
  – Allows wavelength reuse

- EVA/MMU and STS or co-orbiter links are never simultaneous, but EVA/MMU and OMV links can be simultaneous

- EVA/MMU terminals are equipped with two wavelength pairs

  – Any two astronauts can transmit/receive at distinct wavelength pairs

255

PROX-OPS WAVELENGTH PLAN

This chart summarizes the assigned Prox-Ops wavelengths, based on the assumptions described on the previous chart. The resultant 10-nm spacing should allow for sufficient reduction of inter-user interference.

256

PROX-OPS WAVELENGTH PLAN

- GaAlAs diode lasers in 780 to 870 nm wavelength range
- 10 Prox-Ops wavelengths implies 10-nm spacing
- Wavelengths assigned to facilitate T/R separation on each vehicle

Vehicle \ Wavelength (nm)	780	790	800	810	820	830	840	850	860	870
EVA/MMU #1		R					T			
EVA/MMU #2					R					T
FTS				R					T	
MSC			R					T		
OMV	R					T				
STS	R					T				
Co-Orbiter	R					T				

R = receive wavelength,   T = transmit wavelength.

257

PROX-OPS WAVELENGTH PLAN (cont.)

This chart presents another pictorial summary of the Prox-Ops wavelength assignments.

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PROX-OPS WAVELENGTH PLAN (cont.)

	OMV/R STS/R COP/R	EVA #1/R MSC/R	FTS/R EVA #2/R	OMV/T STS/T COP/T	EVA #1/T MSC/T	FTS/T EVA #2/T
780 nm	790 nm	800 nm	810 nm	820 nm	830 nm	840 nm	850 nm	860 nm	870 nm
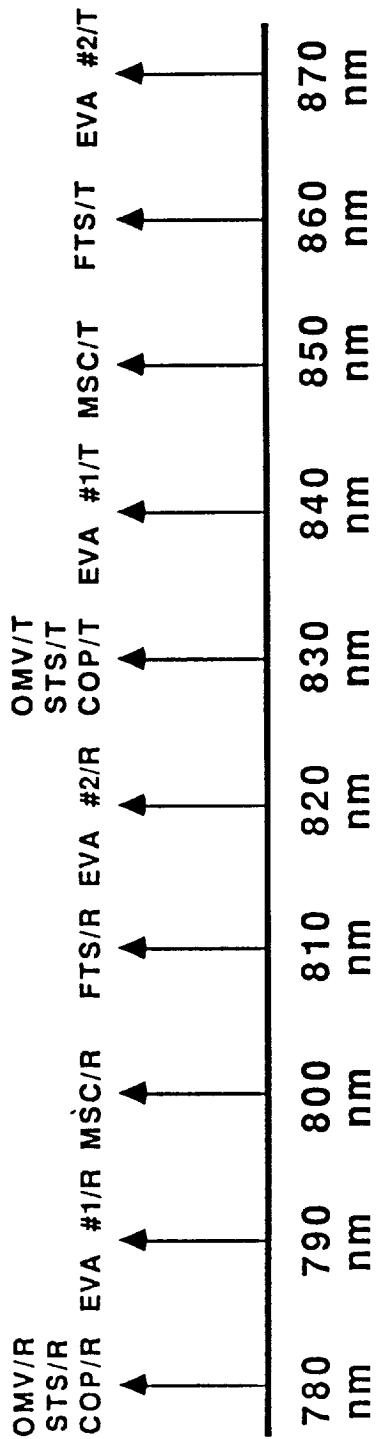
- R = receive wavelength; T = transmit wavelength

- OMV, STS, and co-orbiters reuse same wavelength pair since assumed never simultaneous

259

PROX-OPS DESIGN SUMMARY

The next two charts summarize the design parameters for the various Prox-Ops optical terminals discussed on earlier charts. The table on this chart provides information on the transmit/receive wavelength assignments, laser and detector count, and fine pointing technique.

PROX-OPS DESIGN INCLUDES A VARIETY OF OPTICAL TERMINALS

Terminal	# Lasers *	Transmit/Receive Wavelengths (nm)	# Detectors	Fine Pointing Mirror
Space Station	2	Several at each vehicle wavelength	1	YES
OMV	2	830/780	1	YES
STS	2	830/780	1	YES
Co-orbiters	2	830/780	1	YES
EVA/MMU	4	840/790, 870/820	2	YES
FTS	2	860/810	1	NO
MSC	2	850/800	1	NO

* One redundant laser assumed at each wavelength

PROX-OPS DESIGN SUMMARY (cont.)

This chart concludes the Prox-Ops optical terminal design summary, including such items as aperture diameter, special terminal items, and SWAP estimates. SWAP estimates are based on the discussions found on earlier charts, and have been rounded up to the nearest 250 cc, 0.5 lb, and 5W.

PROX-OPS DESIGN INCLUDES A VARIETY OF OPTICAL TERMINALS (cont.)

Terminal	APERTURE (cm)*	Special Terminal Items	Volume (cm³)	Mass (kg)	Power (W)
Space Station	10	--	5750	11	55
OMV	10	--	5750	11	55
STS	10	--	5750	11	55
Co-orbiters	10	--	5750	11	55
EVA/MMU	1	2 Detector-cube coarse acq. sensors	4000	7.5	55
FTS	1	2 Detector-cube coarse acq. sensors	3000	6.5	40
MSC	1	2 Detector-cube coarse acq. sensors	3000	6.5	40

* Gimballed telescope with Coude' optical path assumed for all to reduce mass

SYSTEM ACQUISITION AND OBSCURATIONS

This chart presents several of the system issues relating to LOS obscurations in Prox-Ops, and their impact on the system design. The next several charts supplement this one by describing antenna handover sequences that cope with the obscurations. The systems issues summarized on this chart have been described on several earlier charts. Full-spherical coverage (as necessary) is provided despite SSF interference by mounting duplicate terminals on the front and back, with each terminal providing hemispherical coverage. This approach pertains to the long-range vehicles, and the EVA/MMU when it is away from SSF. FTS and MSC communication is supported by terminals placed at both ends of, and possibly in the middle of, the MSC track. The SSF terminal count is therefore not very large, provided coverage to the EVA/MMUs is provided by a tethered link when they remain very near SSF.

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SYSTEM ACQUISITION AND OBSCURATIONS

- Wavelengths are assigned to vehicles and space-division multiplex used to maintain four simultaneous two-way links

- Vehicle-Space Station links are independent, allowing simultaneous mutual acquisition; Space Station computer controls system operation

- Multiple terminals used on Space Station to cope with obscurations and provide desired angular coverage

  - Terminals mounted on mast to minimize obscurations
  - First-cut design of terminal layout:

    -- Long-range vehicles (OMV, STS, Co-orbiters) require at least two terminals--front & back coverage
    -- FTS and MSC require terminals near each end of the track, and possibly in the middle
    -- EVA/MMU -Two simultaneous links increases availability, but may be precluded by severe weight restrictions; Away from Space Station - 2 each for front & back coverage, Near Space Station - many obscurations, tether may be best

PROX-OPS OPTICAL COMMUNICATIONS BLOCK DIAGRAM

This chart pictorially summarizes the Prox-Ops mission, including the wavelength assignments. As shown and described on earlier charts, system operations are controlled by a SSF-based computer.

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PROX-OPS OPTICAL COMMUNICATIONS
BLOCK DIAGRAM

EVA/MMU

EVA/MMU

OMV

$\lambda = 780,830$ nm

$\lambda = 790,840$ nm

$\lambda = 790,840$ nm

$\lambda = 820,870$ nm

$\lambda = 820,870$ nm

$\lambda = \begin{cases} 810,860 \text{ nm for FTS} \\ 800,850 \text{ nm for MSC} \end{cases}$

MSC/FTS

Space
Station

Computer

STS or
Co-orbiter

$\lambda = 780,830$ nm
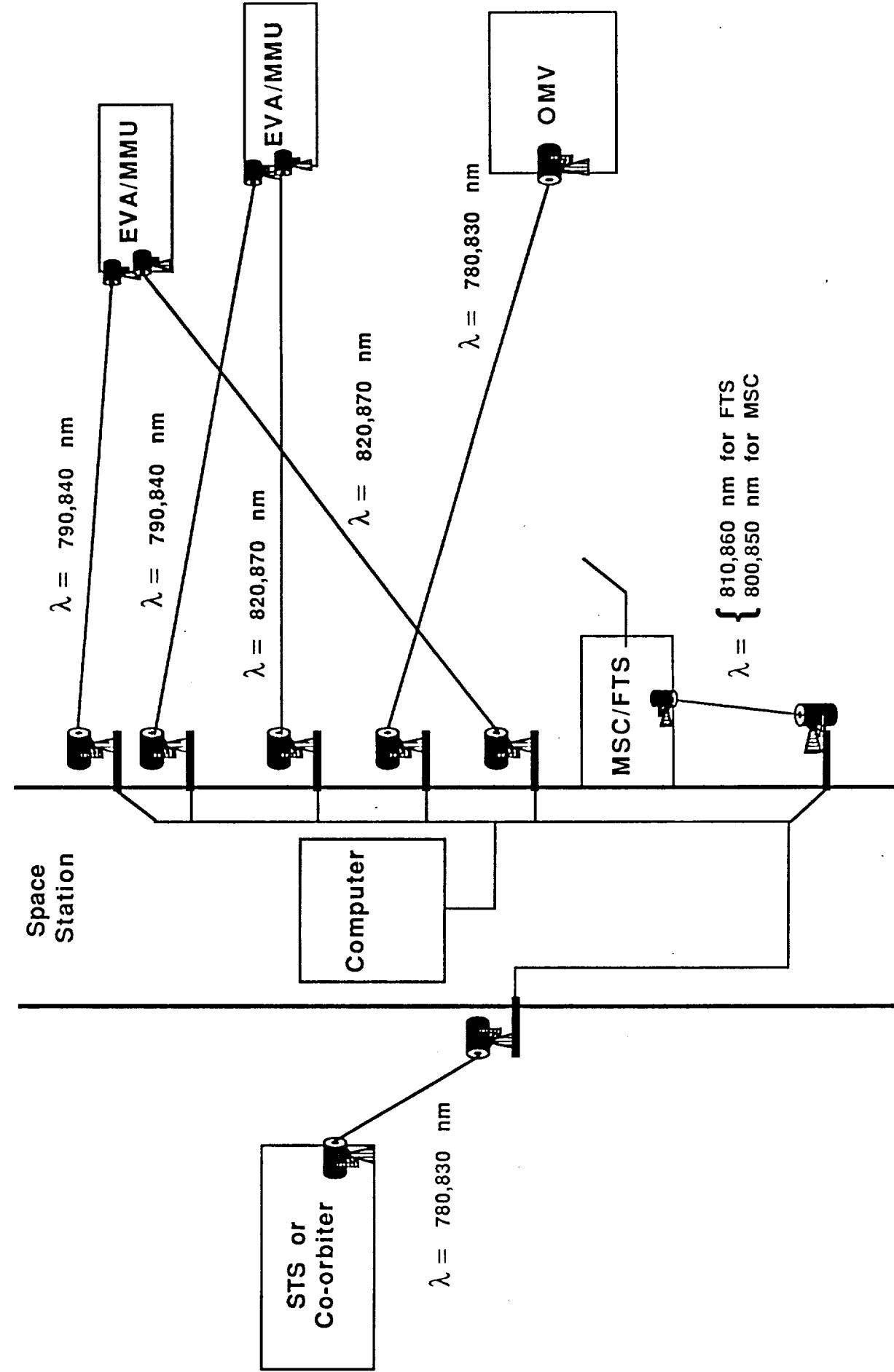
SPACE STATION CONTROLS ANTENNA HANDOVER

The next several charts discuss antenna handover techniques that allow Prox-Ops to cope with anticipated LOS obscurations. The key to the design is that obscuration times are known in advance, allowing the system to prepare for dynamic switching, and thus minimize down-time. Down-time is avoided altogether if two vehicle-based terminals are available that allow establishment of a back-up link before the operating link is fully obscured. The disadvantage with this approach is obviously payload weight. Vehicle weight impact is reduced with only one vehicle-based terminal, but this implies a short down-time to allow the vehicle terminal to slew between the operating and back-up SSF-based terminals.

SPACE STATION CONTROLS ANTENNA HANDOVER

- Assumptions: Obscuration times are known by Space Station computer
  Second terminal has clear line of sight to vehicle
  before first terminal is completely obscured

- Two terminals on vehicle eliminates down time

- One terminal on vehicle implies short down time
  to allow slewing between Space Station terminals

269
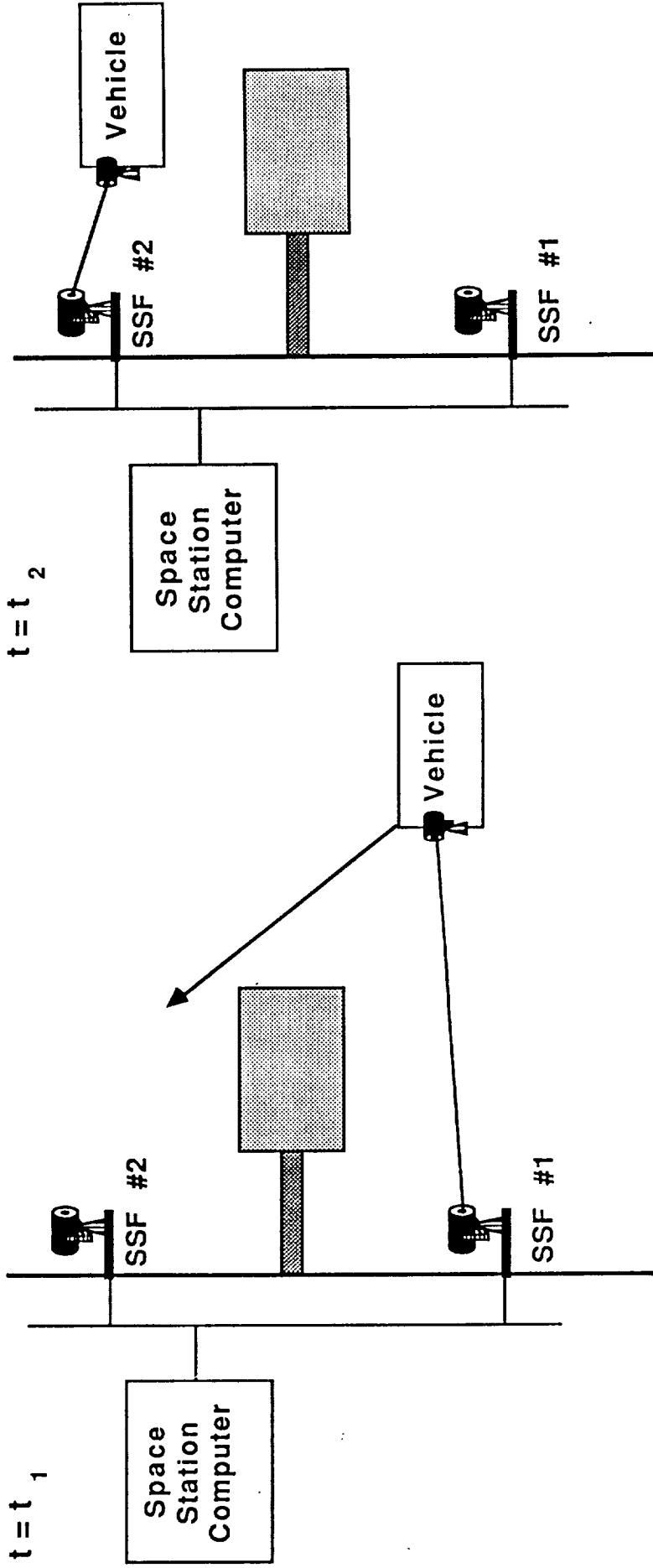
ANTENNA HANDOVER – ONE VEHICLE TERMINAL

This chart details the antenna handover sequence when one vehicle-based terminal is available, including the applicable time line. The SSF terminal locations are selected to reduce slew time, while satisfying the criteria that the second terminal have a clear line of sight to the vehicle before the SSF-vehicle link-up is completely obscured. With the assumed 10-deg/sec slew rate, it is anticipated that both conditions can be readily achieved.

# ANTENNA HANDOVER - ONE TERMINAL ON VEHICLE

- At $t = t_1$

  Two-way tracking and communications established between Space Station terminal #1 (SS #1) and vehicle terminal (VT)

  Space Station computer has knowledge of upcoming obscuration and
  – Sends activation command and SS #2 angular position to VT
  – Sends activation command and vehicle angular position to SS #2

- At $t_1 < t < t_{obs}$

  SS #2 points beacon at vehicle and waits for return
  Space Station computer continually updates positional information to both
  Computer sends command to vehicle to slew from SS #1 to SS #2
  Coarse acquisition cube on vehicle can be used to provide initial SS #2 position
  Vehicle slews to SS #2 (slew rate $\approx$ 10 deg/sec), and mutual acquisition is completed
  Computer commands SS #1 to stop pointing at VT

271

Timeline markers: $t = t_1$ $t = t_{obs}$ (SS #1 obscured) $t = t_2$

SS #1	Track and COMM w/ VT	Point at VT		
VT	Track and COMM w/ SS #1	ACQ	Track and	COMM w/ SS #2
SS #2	Point at VT	ACQ	Track and	COMM w/ VT

VT slew from SS #1 to SS #2
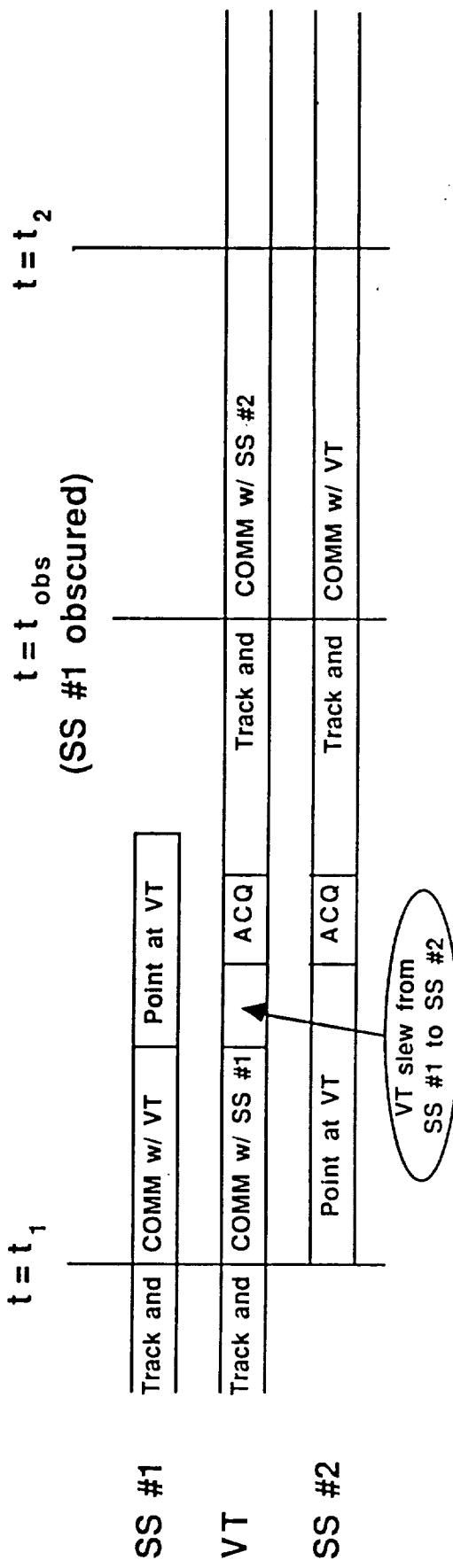
ANTENNA HANDOVER – TWO VEHICLE TERMINALS

This chart details the antenna handover sequence when two vehicle-based terminals are available, including the applicable time line. This approach allows handover without a down time, provided the SSF terminals satisfy the criteria that the second terminal have a clear line of sight to the vehicle before the original SSF-vehicle link is completely obscured. Due to the relatively small payload impact of a single Prox-Ops optical terminal, the additional payload impact associated with this approach may be acceptable for several of the larger Prox-Ops vehicles (e.g., OMV, STS). Its use on the EVA/MMU might be precluded because of weight restrictions, but certainly offers significant system advantages by reducing the probability of entering into the coarse-acquisition mode.

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ANTENNA HANDOVER - TWO TERMINALS ON VEHICLE

- At $t = t_1$

  Two-way tracking and communications established between
  Space Station terminal #1 (SS #1) and vehicle terminal #1 (VT #1)

  Space Station computer has knowledge of upcoming obscuration and

  - Sends activation command and SS #2 angular position
    to VT #1 for on-board distribution to vehicle terminal #2 (VT #2)
  - Sends activation command and vehicle angular position to SS #2

- At $t_1 < t < t_{obs}$

  SS #2 and VT #2 point beacons at each other and rapidly complete mutual acquisition

	$t = t_1$	$t = t_{obs}$ (SS #1 obscured)	$t = t_2$
SS #1	Track and COMM w/ VT #1		
VT #1	Track and COMM w/ SS #1		
SS #2	ACQ	Track and COMM w/ VT #2	
VT #2	ACQ	Track and COMM w/ SS #2	

273
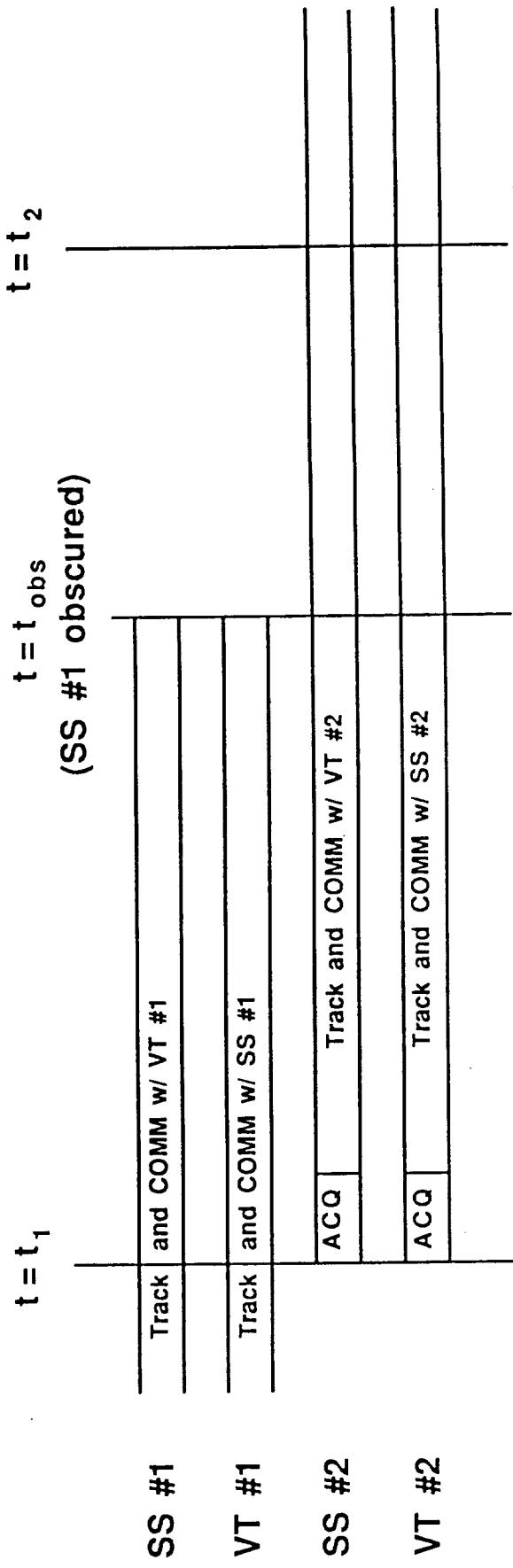
# SPACE STATION MODEL – PHASE I CONFIGURATION

The next series of charts give detailed drawings of SSF and the Prox-Ops optical terminals, progressing from the entire SSF configuration to the placement and relative size of the optical terminal. The first chart shows the baseline Phase I SSF configuration assumed for this study, including its physical dimensions.

All Prox-Ops optical terminals will necessarily be mounted in the 110-m section between the two alpha joints.

274

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SPACE STATION MODEL -PHASE I CONFIGURATION
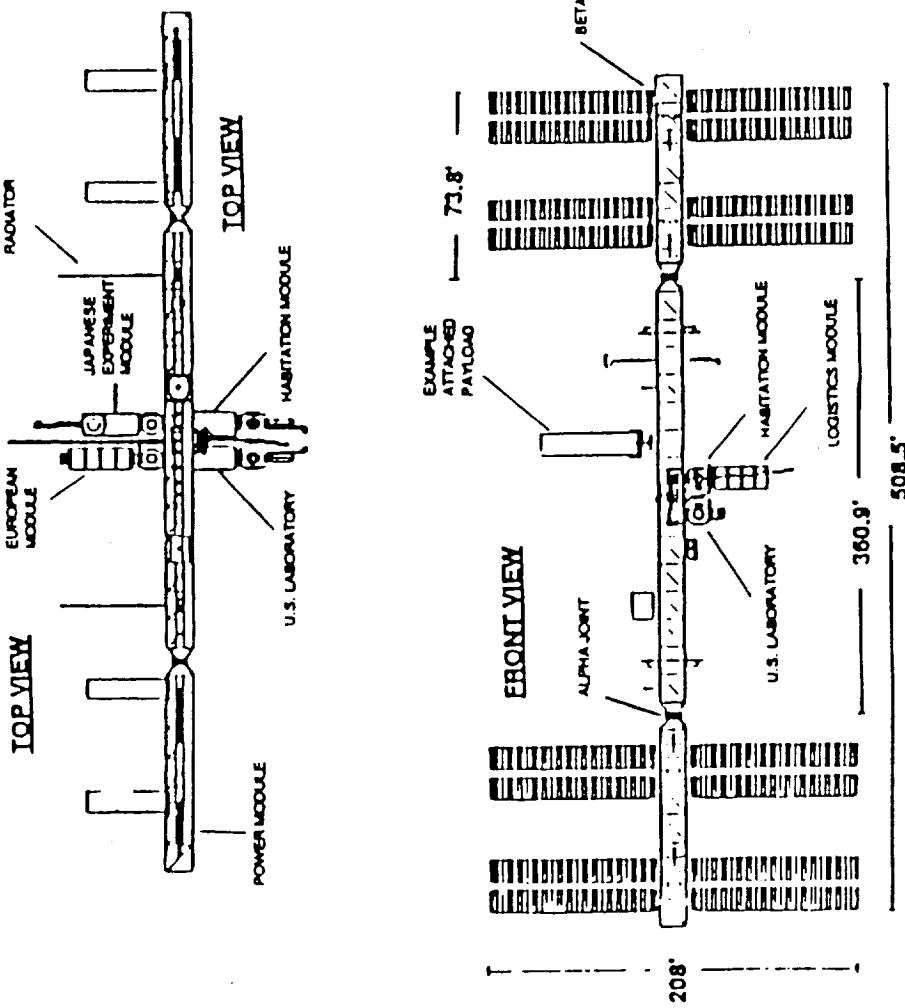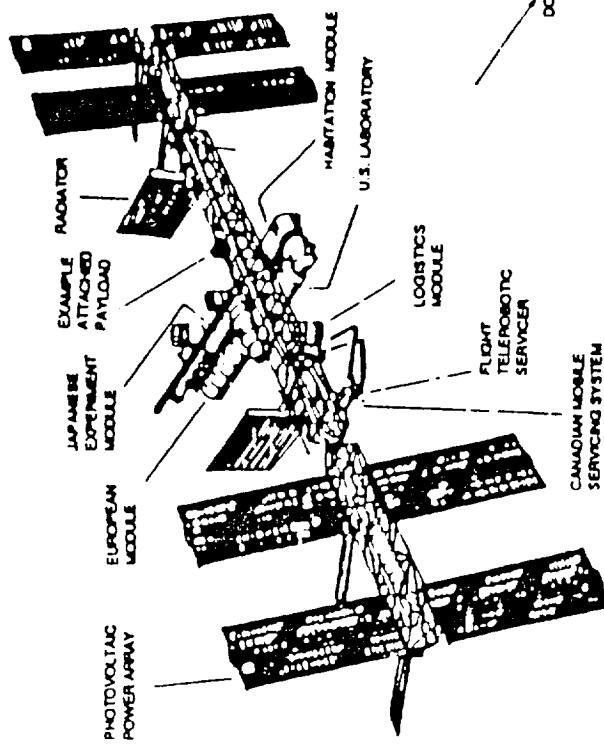
Diagrams from: Space Station WP3 APAE User Handbook
General Electric Astro-Space Division
October 1988

SPACE STATION MODEL – ATTACHED PAYLOAD AREA

This sketch shows an expanded view of the 110-m attached payload section between the two SSF alpha joints, showing several example payloads.

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SPACE STATION MODEL -
# EXPANDED VIEW OF ATTACHED PAYLOAD AREA
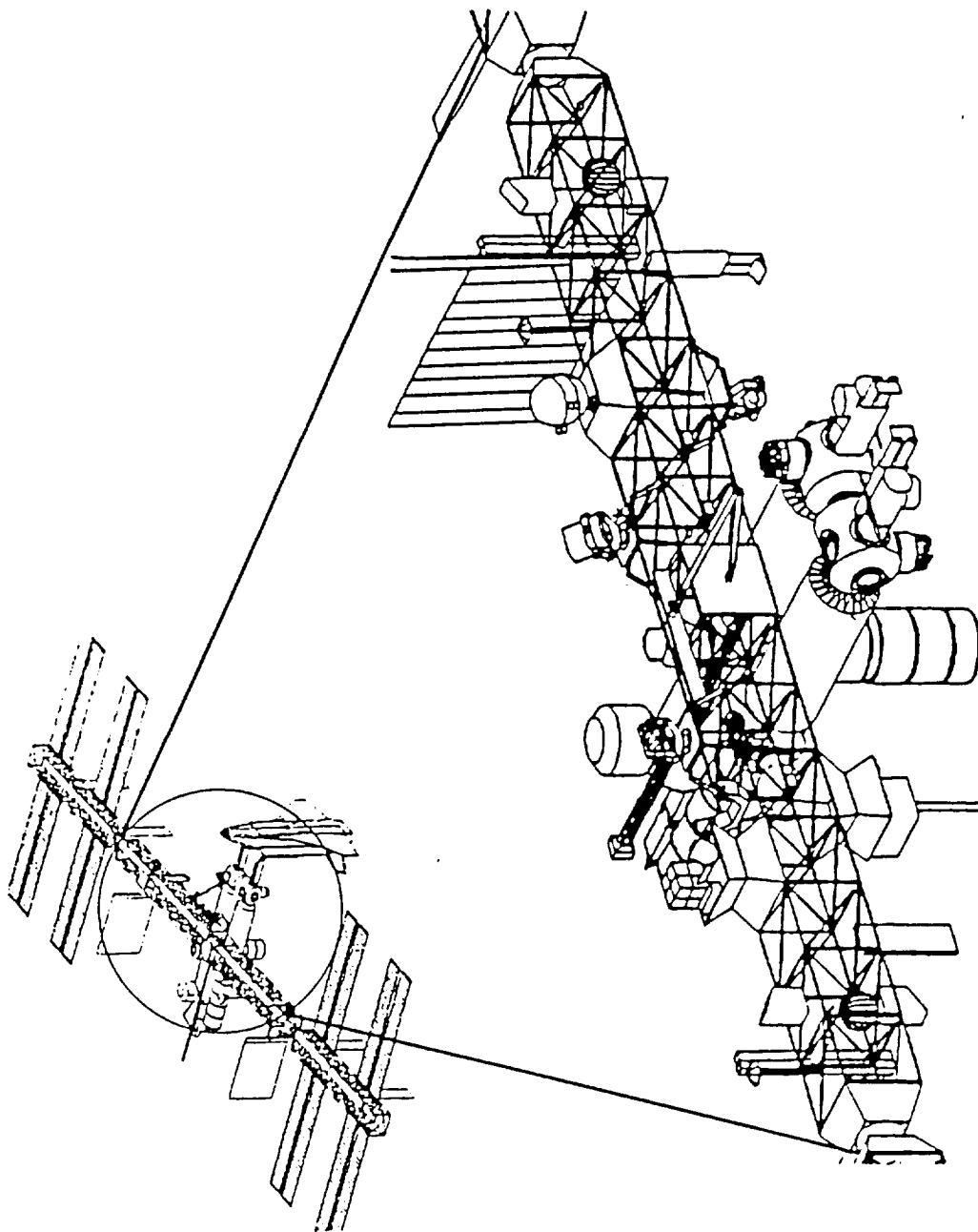
SPACE STATION MODEL – ATTACHED PAYLOAD AREA (cont.)

This sketch shows a further expanded view of the truss cross-section measuring approximately 5-meters-cube. Also shown is an attached optical terminal indicating its relative size.

SPACE STATION MODEL -
# EXPANDED VIEW OF ATTACHED PAYLOAD AREA (cont.)
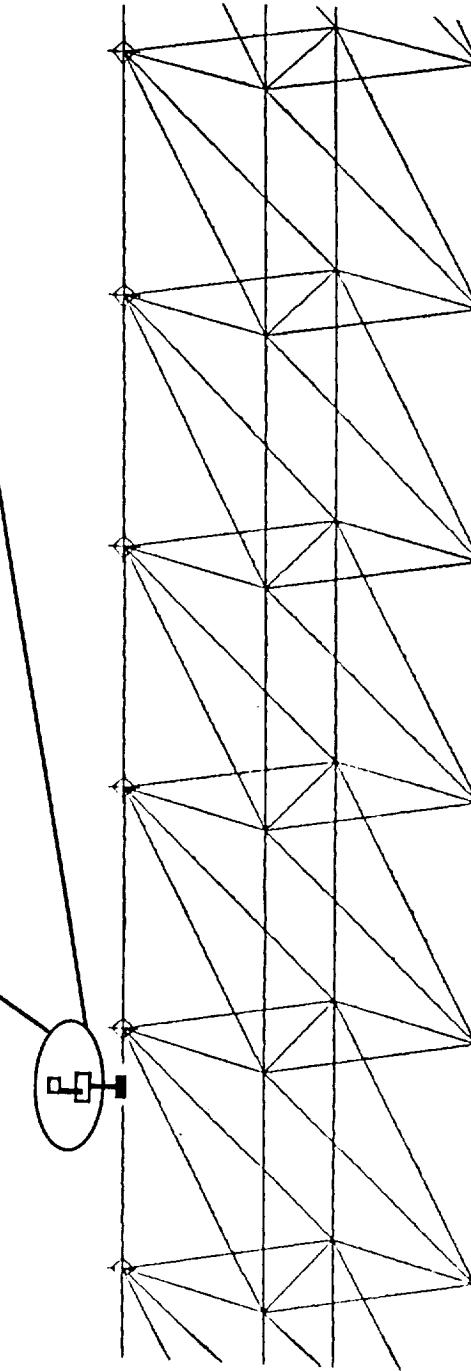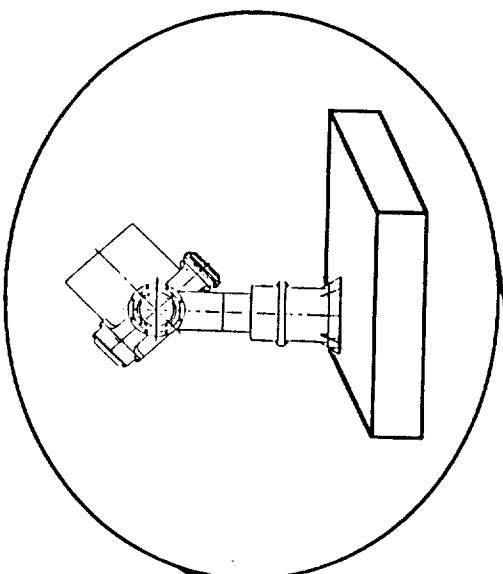
SPACE STATION MODEL – ATTACHED PAYLOAD AREA (cont.)

The final sketch shows an even further expanded view of the truss cross-section and attached optical terminal. The conclusion from these drawings is that the optical terminal is a rather miniscule addition to the SSF attached payload area, even though, as discussed, several such terminals are required to support the desired mission. In fact, the optical terminal designs discussed in this study present an insignificant payload impact to all vehicles, with the possible exception of the EVA/MMU.

SPACE STATION MODEL -
EXPANDED VIEW OF ATTACHED PAYLOAD AREA (cont.)
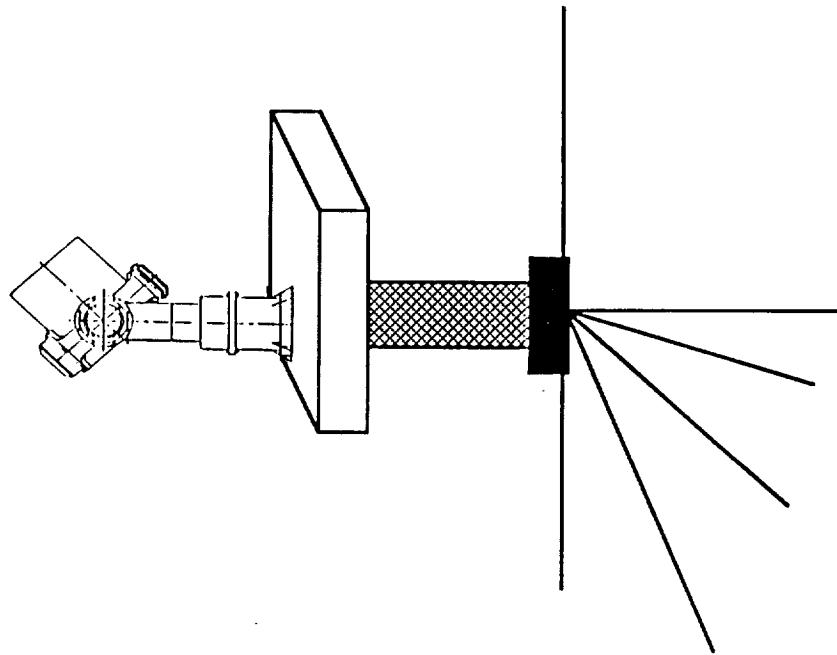
7.0 CONCLUSION

The section addresses the items indicated that include a brief design summary, identification of technological strain areas imposed by an optical Prox-Ops, assessment of the impact of anticipated technical advances on the strain areas, and recommendations for follow-on work to transition the results of this study effort to operation-ready status.

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7.0 CONCLUSION

- Design summary and technological strain areas

- Impact of technology advances

- Recommended follow-on efforts

283

OPTICAL PROX-OPS STRAIN AREAS

A design has been described that satisfies the initial-phase and growth-phase Prox-Ops requirements. By so doing, several stressing design areas have been identified and are summarized on this chart. Each of the areas have been addressed throughout the report, and design solutions have been proposed that solve the demanding requirements in these areas. Combining the various analysis results has provided an optical system design with fairly small payload impact. Key to this effort were the relatively low data rates and short ranges in Prox-Ops that allowed a single quadrant detector to support acquisition, fine tracking, and communications, provided the acquisition FOU is controlled through a specified operational scenario.

284

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OPTICAL PROX-OPS TECHNOLOGY STRAIN AREAS

- Strawman design described in this report satisfies the long-range and short-range Prox-Ops requirements

- Design has identified several difficulties for an optical Prox-Ops:

  - Fast acquisition with a large FOU
  - Spherical angular coverage despite line-of-sight obscurations
  - Multiple access to a variety of vehicles
  - Wide detector FOV and the impacts of receive optical background and optical design (f/# limitations)
  - Combining ACQ, track, and COMM functions on a single detector reduces complexity and SWAP, but the subsystems cannot be tailored to their specific and diverse needs

285

IMPACT OF TECHNOLOGY ADVANCES

This chart summarizes those areas where future technical advances could potentially reduce the complexity and SWAP impact of an optical Prox-Ops, and identifies those areas likely to remain as design drivers despite these developments. Summarizing, although advances are expected in the transmitter, receiver, and beam-pointing subsystems, Prox-Ops remains a challenging application for optical technologies, because it requires multiple access to several vehicles over an essentially full-spherical field of regard, while coping with unavoidable LOS obscurations. Furthermore, reliable communications to the EVA/MMU with its anticipated irregular platform disturbance spectrum is a difficult task indeed.

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IMPACT OF TECHNOLOGY ADVANCES ON OPTICAL PROX-OPS

- Conservative design approach used to reduce risk

  - Available optical components assumed in link assessments

- Technical advances are expected in the areas of

  - High-power diode laser transmiters - higher power, longer life, better beam quality, etc.
  - Low-noise detectors and receivers
  - Lightweight pointing mechanisms

  that could conceivably reduce the complexity and SWAP of the Prox-Ops optical terminals

- Despite these advances, several key design drivers will remain:

  - Optical links favor narrow beams and small FOVs
  - Large detector FOVs imply large background shot noise in a direct-detection system; Optical design constraints (f/#) also remain
  - Line-of-sight obscurations near SSF will always be a formidable problem
  - Multiple-access over large (e.g., hemispherical) field of regard demands multiple optical terminals

RECOMMENDED FOLLOW-ON EFFORTS

The design presented has assumed available optical components to reduce system complexity and risk. This process has uncovered several key technical areas where a solution was proposed, but where some technical effort is required to prove the particular concepts. These areas are considered to be the only risks in implementing an optical Prox-Ops, and form the basis for recommended follow-on efforts.

The first area tackles the difficult question of what is the best system approach for Prox-Ops, and a firm conclusion can only be reached by investigating all pertinent system-level issues: performance, SWAP, complexity, cost, etc. The design presented here satisfies the Prox-Ops requirements, but a full system-level comparison is required between optical, RF, and hybrid solutions to define the optimal approach.

The second follow-on effort concentrates on the coarse-acquisition sensor that became an integral part of the design. Simply put, the detector cube sensor was the key component that solved the most demanding requirements, interfacing with the baselined laser communication terminal to provide rapid acquisition under worst-case conditions. The scope of this report ends with definition of the concept, and further work is needed to prove the concept under simulated link conditions.

The third item could potentially improve the terminal performance for the long-range Prox-Ops links, where far-field power density limitations and the receive backgrounds in the wide FOVs needed to support acquisition began to impact the design. The result was that a single quadrant detector sometimes could not support the ACQ, track, and COMM requirements. A CID array detector was often suggested as a candidate to provide the desired performance under such large-receive-background conditions, but the question remains as to whether this selection entails separate ACQ/track and COMM detectors, or can the CID array perform all three functions. The CID detector approach is precluded on SSF by bandwidth limitations, but has potential on the vehicles with their 0.5-Mbps receive data rate.

The final follow-on effort takes a close look at the tradeoff between a tethered and free-space link when communicating very near SSF where LOS obscurations are prevalent.

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RECOMMENDED FOLLOW-ON EFFORTS

- Detailed system tradeoff of RF vs optical vs hybrid Prox-Ops

  - Is an optical approach preferred across the board, despite the design difficulties uncovered during this study?
  - Optical links prefer narrow beams and small FOVs; best suited to the long-range Prox-Ops links
  - Strawman design meets the short-range, multiple-access Prox-Ops, but is it the "best" solution?

- Detailed analysis and "field test" of coarse acquisition detector cube

  - Experimentally verify performance assessments in this report, particularly under worst-case optical background conditions
  - Measure performance under extreme grazing incidence
  - Explore phase-sensitive detection techniques to improve sensitivity

- Detailed experimental assessment of CID array detector for ACQ, TRK, and 500-kbps COMM

- Detailed assessment of obscuration problem near SSF

  - Determine terminal count and location that provide spherical coverage despite the numerous obscurations
  - Tradeoff tether vs free-space link near SSF

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9.0 LIST OF ACRONYMS

ACQ	Acquisition
AGC	Automatic gain control
APD	Avalanche photodiode
AQC	Avalanche quad cell
BER	Bit error rate
BG	Background
BPPM	Binary pulse position modulation
bps	Bits per second
BSR	Beam size ratio
CCD	Charge-coupled device
CID	Charge-injection device
COMM	Communication
COP	Co-orbiting platform
CW	Continuous wave
EVA/MMU	Extra Vehicular Activity/Manned Maneuvering Unit
FOU	Field of uncertainty
FOV	Field of view
FTS	Flight Telerobotics Servicer
FWHM	Full-width at half maximum
GaAlAs	Gallium aluminum arsenide
GPS	Global Positioning System

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9.0 LIST OF ACRONYMS (cont.)

LEC	Lateral effects cell
LED	Light emitting diode
LOS	Line of sight
MSC	Mobile Servicing Center
NA	Numerical aperture
Nd:YAG	Neodymium-doped yttrium aluminum garnet
NSTS	National Space Transportation System (Space Shuttle)
OMV	Orbital Maneuvering Vehicle
PIN	p-type - intrinsic-type - n-type photodiode
Prox Ops	Proximity operations
RF	Radio frequency
RMS	root mean square
Si	Silicon
SIM	Sinusoidal intensity modulation
SNR	Signal-to-noise ratio
SS	Space Station
SSF	Space Station Freedom
SWAP	Size, weight, and power
STS	Space Transportation System (Space Shuttle)

C-4

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9.0 LIST OF ACRONYMS (cont.)

T/R	Transmit/receive
TRK	Track
TT&C	Telemetry, tracking, and command
VT	Vehicle terminal
WDM	Wavelength-division multiplexing

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TASK 6 FINAL REPORT

16. Abstract

This report is the result of a study performed to determine the feasibility of using optical technology to perform the mission of the proximity operations communications subsystem on Space Station Freedom. In this report, proximity operations mission requirements are determined and the relationship to the overall operational environment of the space station is defined. From this information, the design requirements of the communication subsystem are derived. Based on these requirements, a preliminary design is developed and the feasibility of implementation determined. To support the Orbital Maneuvering Vehicle and National Space Transportation System, the optical system development is straightforward. The requirements on extra-vehicular activity are such as to allow large fields of uncertainty, thus exacerbating the acquisition problem; however, an approach is given that could mitigate this problem. In general, it is found that such a system could indeed perform the proximity operations mission requirement, with some development required to support extra-vehicular activity.

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