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PROCEEDINGS OF THE

RENDEZVOUS AND PROXIMITY OPERATIONS WORKSHOP

FEBRUARY 19-22, 1985

VOLUME IV

SESSIONS 9 – 11

NASA

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Lyndon B. Johnson Space Center

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PROCEEDINGS -

RENDEZVOUS AND PROXIMITY OPERATIONS WORKSHOP

HOSTED BY

NASA LYNDON B. JOHNSON SPACE CENTER
NASSAU BAY HILTON HOTEL
HOUSTON, TEXAS
19 - 22 FEBRUARY 1985

VOLUME IV - PRESENTATIONS FROM SESSIONS 9 THROUGH 11

PREPARED BY: Kenneth J. Cox
KENNETH J. COX
WORKSHOP ORGANIZER

27 MARCH 1985

VOLUME IV - PRESENTATIONS FROM SESSIONS 9 THROUGH 11

Due to the large quantity of information contained in the eleven sessions of the Rendezvous and Proximity Operations Workshop, the presentation material has been assembled into three volumes for the Proceedings. These three volumes (Volumes II - IV) are in addition to the Executive Summary (Volume I), which was published and distributed on 27 February 1985.

- Volume I - EXECUTIVE SUMMARY, 27 February 1985
- Volume II - PRESENTATIONS FROM SESSIONS 1 THROUGH 5A
- VOLUME III - PRESENTATIONS FROM SESSIONS 5B THROUGH 8
- VOLUME IV - PRESENTATIONS FROM SESSION 9 THROUGH 11

An itemized list of the presentations and authors precedes each of the Sessions in this volume.

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SESSION 9 - CONTROLS

9-1. "Control Technology Related to Rendezvous and Proximity Operations (An Overview)" - R. Oglevie and W. Schleich/ Rockwell International

9-2. "RCS Architectural Issues for Space Vehicle Rendezvous and Proximity Operations" - E. Bergmann, S. Croopnick, and K. Daly/CSDL

9-3. "Retrieval of Tumbling Satellites" - A. Ray/MMC (Presentation was narration of slides, which were not amenable to hard copy reproduction)

9-4. "Thruster-Assisted Tethers for Rendezvous and Proximity Operations" - R. Laskin/JPL

9-5. "Controllability Issues for Remotely-Piloted Vehicles" - R. Dabney/NASA MSFC

9-6. "Simulation of the Last Meters of Approach and Docking" - B. Claudinon/MATRA

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SPACE STATION

Control Technology Related to Rendezvous and Proximity Operations (an Overview)

Presented to NASA Rendezvous and Proximity Operations Workshop

February 19-22, 1985

R.E. Oglevie
W.T. Schleich

Rockwell International
Space Station Systems Division

9-2

OVERVIEW AND SUMMARY

The purpose of this presentation is to examine the historical evolution of Rendezvous and Proximity Operations (Proxops) through the present time, assess the current technology readiness to meet near future requirements, and to forecast areas of high payoff for future technology development.

The historical review includes Gemini, Apollo, Lunar Module, and the Shuttle Orbiter. It is concluded that these highly successful operations were heavily supported with ground operations, and that the proxops featured a high degree of manual sensing and control. In order to identify advanced technology options the procedure was to identify generic mission phases, their generic functional requirements, and a series of issues that should be considered in designing future missions and flight control systems. Potential solutions to these design issues, including a small family of attractive advanced technology candidates, are identified. It is concluded that virtually all of these candidates are being pursued at some level. Several of these areas are recommended for enhanced funding to reduce the risk associated with achieving the technology readiness need dates imposed by the Space Station and OMV program development schedules. Also, it is recognized that these developments have applicability to many future vehicles and should be focused across a broader range of applications. These recommended candidates include:

- Proxops Sensors
- Rendezvous and Proxops Integration
- Remote Manipulator Systems

It is further recognized that rendezvous and proxops involve a wide variety of technical disciplines, and require careful organization and integration of these disciplines to avoid some of the inherent pitfalls and oversights that can occur in designing these mission phases and systems.

OVERVIEW

SPACE STATION

- MISSION PHASES
- HISTORICAL EVOLUTION OF RENDEZVOUS/ PROXOPS CAPABILITIES
- GENERIC FUNCTIONAL REQUIREMENTS
- DESIGN ISSUES
- TECHNOLOGY OPTIONS
- POTENTIAL TECHNOLOGY DEVELOPMENT CANDIDATES
- CONCLUSIONS & RECOMMENDATIONS

MISSION PHASES

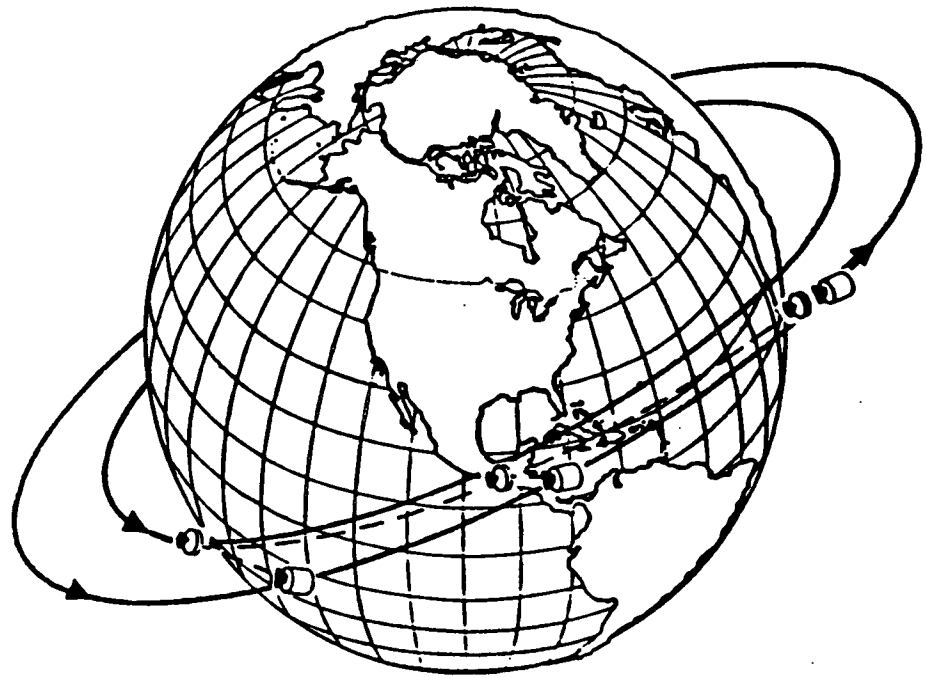
Rendezvous and Proxops missions can be described with the generic missions phases given in the chart.

9-5

MISSION PHASES

SPACE STATION

- ACHIEVEMENT OF RENDEZVOUS COMPATIBLE ORBIT (APPROX COPLANAR)
- PHASING ORBITS
- ORBIT TRANSFER ΔVs
- TERMINAL HOMING
- STATIONKEEPING
- INSPECTION TRAVERSE
- APPROACH TO GRAPPLE/DOCK
- DIRECT DOCK
- GRAPPLING/BERTHING
- DIRECT SEPARATIONS
- MANIPULATOR SEPARATIONS



OVERVIEW

SPACE STATION

- MISSION PHASES
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- CONCLUSIONS & RECOMMENDATIONS

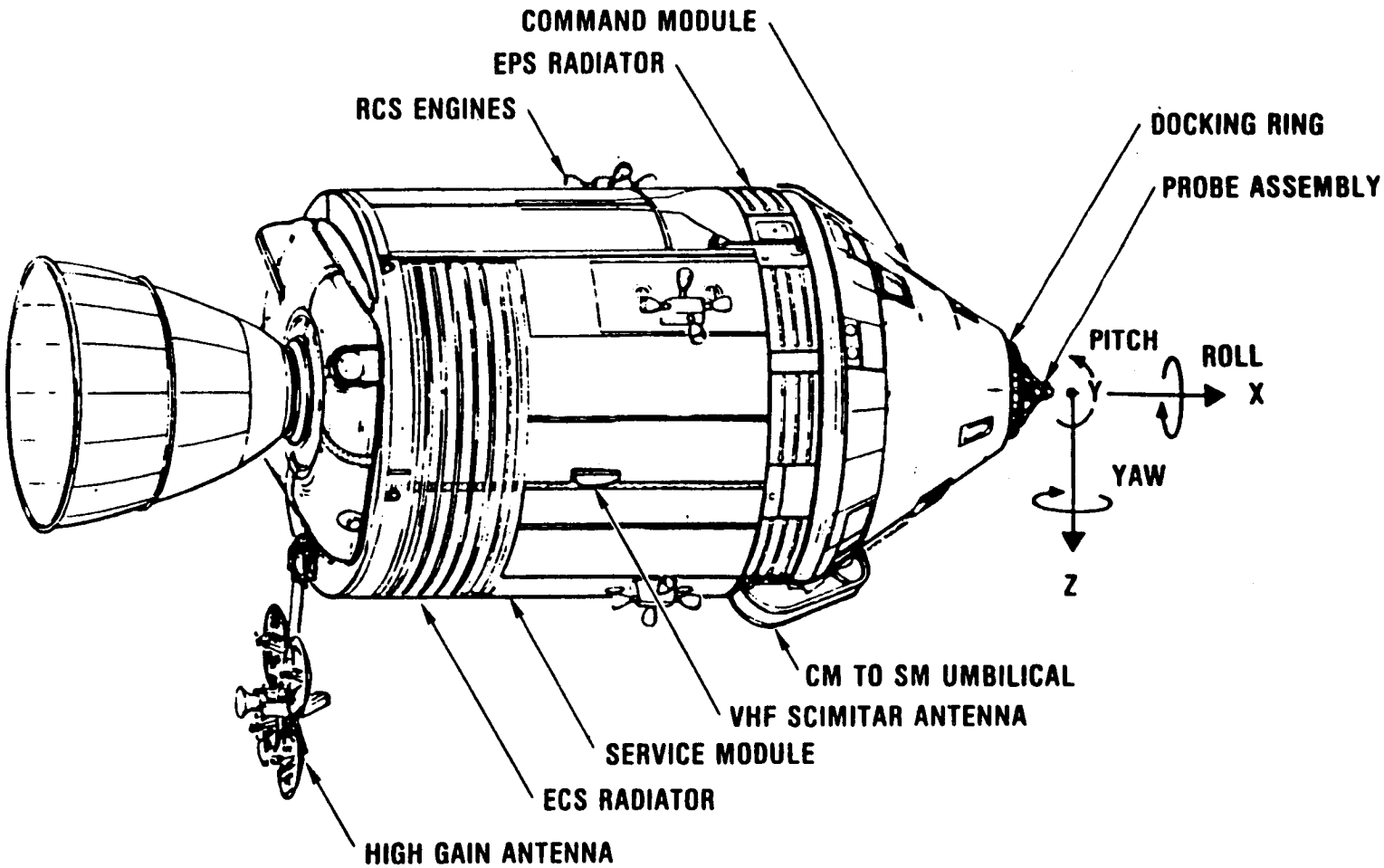
APOLLO CSM CONFIGURATION

The selection of the lunar orbit rendezvous mode for the Apollo lunar landing mission in 1962 provided an impetus for development of rendezvous and docking techniques. The Apollo Command and Service Module (CSM) functions included a docking with the Lunar Module (LM) to extract it from the Saturn V booster stage and the rendezvous and docking with the LM ascent stage following its lift-off from the lunar surface.

The CSM also rendezvoused with the Skylab space station for the three manned visits and with the Soyuz spacecraft in the international Apollo/Soyuz Test Project.

Control for the CSM was provided by four RCS quads located on the circumference of the Service Module. The rendezvous targeting for the CSM was provided by the ground and visual sightings (sextant) on board. The Skylab and LM provided tracking lights to aid visual sightings.

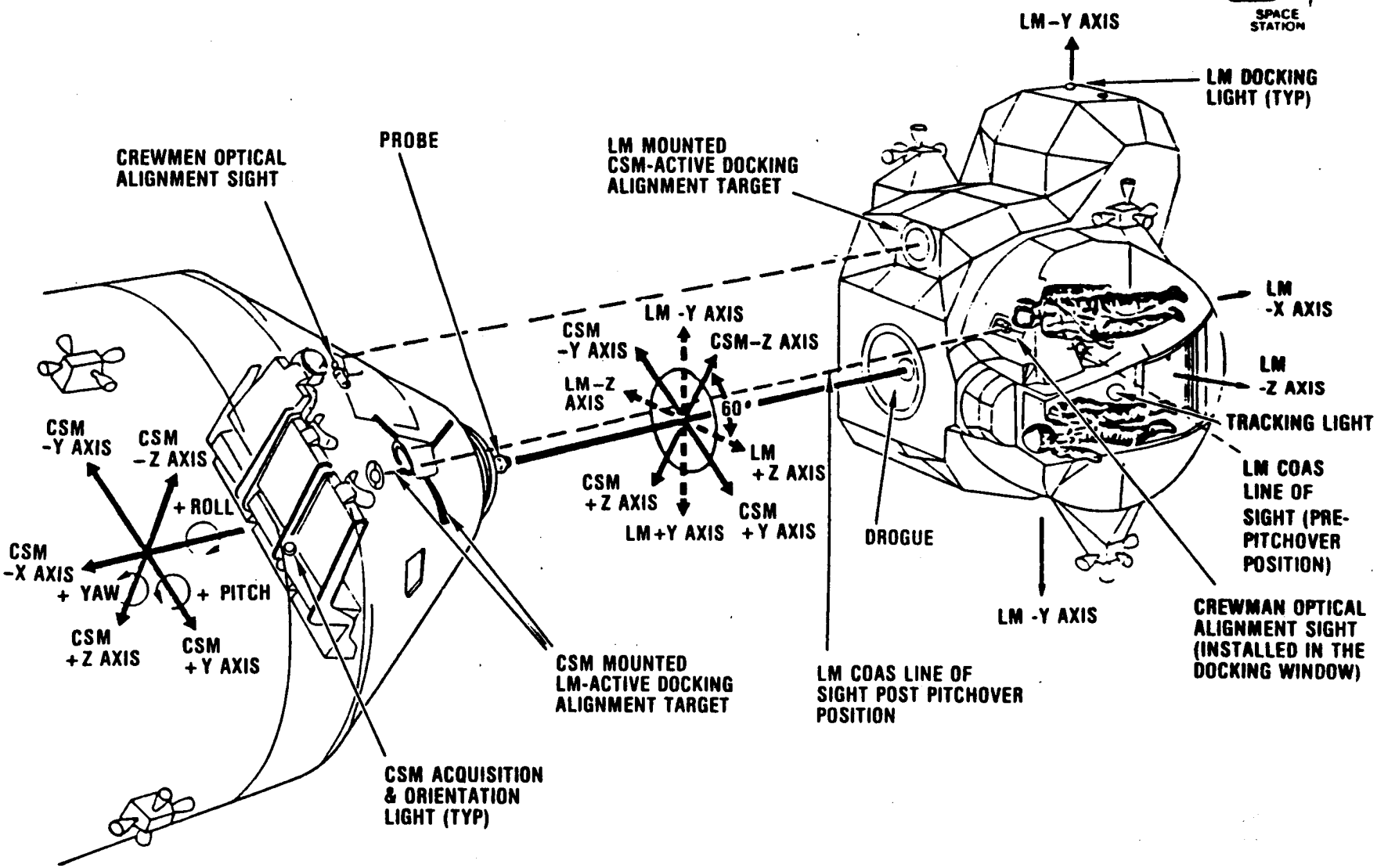
APOLLO CSM CONFIGURATION



APOLLO/LUNAR MODULE DOCKING

The lunar orbit rendezvous was performed with the Lunar Module (LM) providing the active propulsive maneuvering, and radar tracking. The Apollo CSM provided a radar transponder to aid in the tracking. The docking of the two vehicles was performed by the CSM because the lunar module possessed rather high control response at the end of its ascent when its propellant was expended. The relative alignment of the vehicles for docking was performed with visual sensing and manual control. The Crewman Optical Alignment Sight (COAS) and three dimensional alignment aids were employed for this purpose.

APOLLO/LUNAR MODULE DOCKING



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9-11

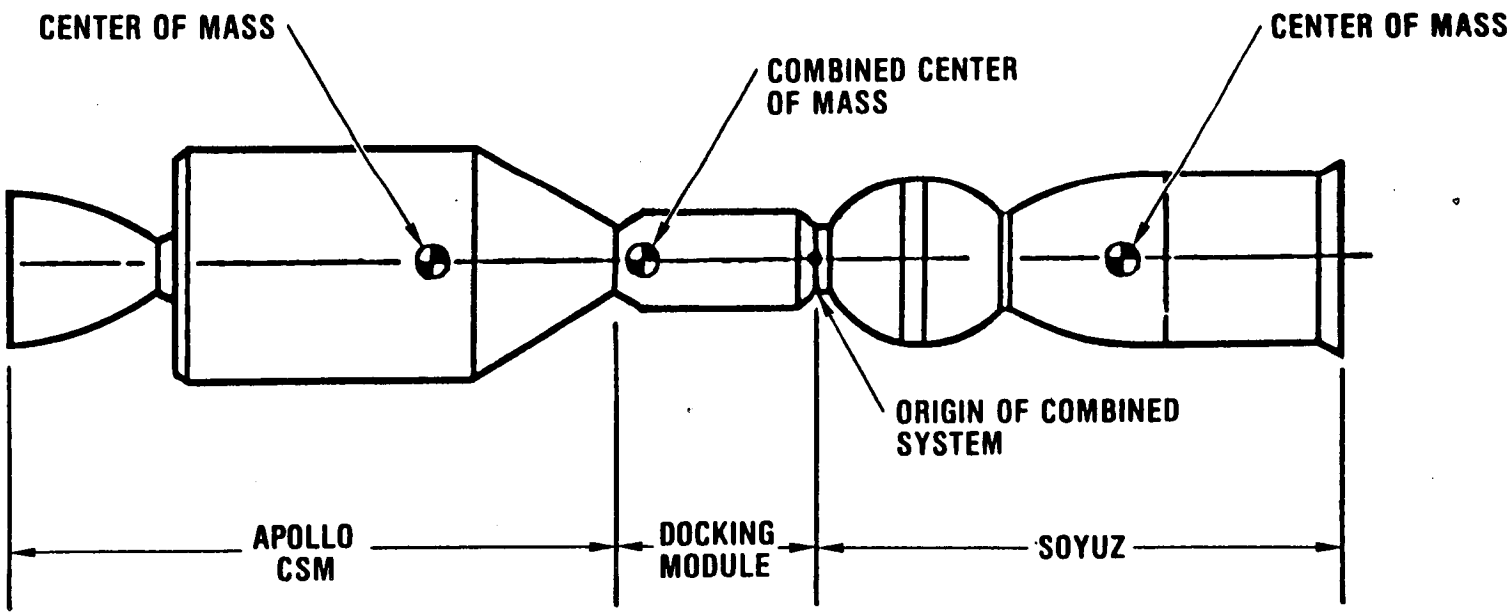
APOLLO SOYUZ COMBINED CONFIGURATION

The combined configuration of the Apollo and Soyuz illustrates the symmetry of the docking situation that was typical of early vehicles. As noted, the center of gravity of the Apollo CSM plus docking module and the Soyuz were on the centerline of the docking interface. The resultant combined center of gravity following docking was also on the same centerline.

9-12

APOLLO SOYUZ COMBINED CONFIGURATION

SPACE STATION



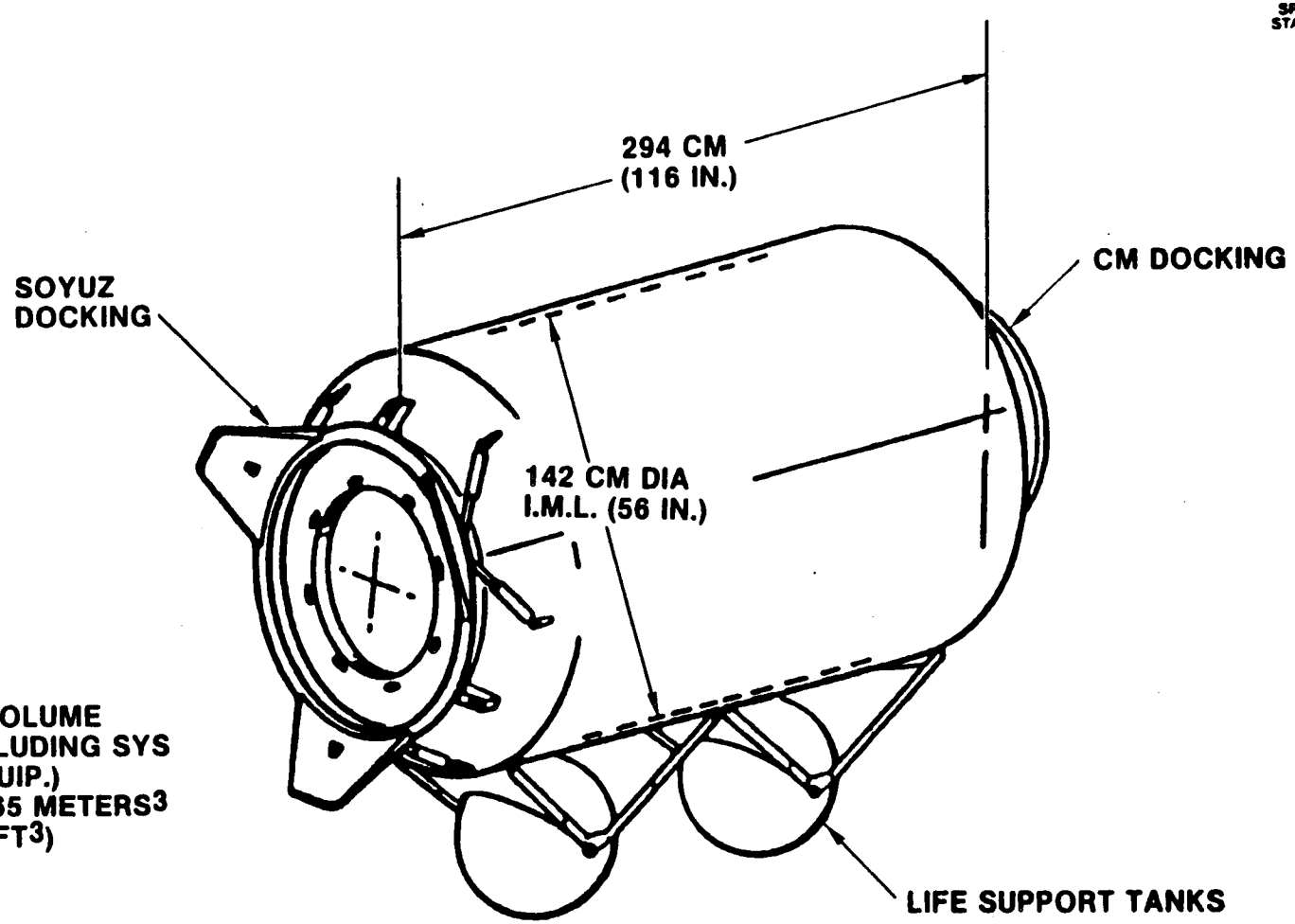
9-13

APOLLO SOYUZ DOCKING MODULE

The Apollo/Soyuz Test Project required creation of a new docking module to interface the different docking systems. The docking module was also required to provide an airlock to adjust for the atmospheric differences between the vehicles. The docking interface was androgenous and can accommodate relatively gross misalignment errors and deviations in contact velocity. Also, transfer through the interface can be accomplished by opening a hatch where the Apollo probe and drogue interface required removal of a hatch plus the probe and drogue prior to crew transfer.

9-14

APOLLO SOYUZ DOCKING MODULE

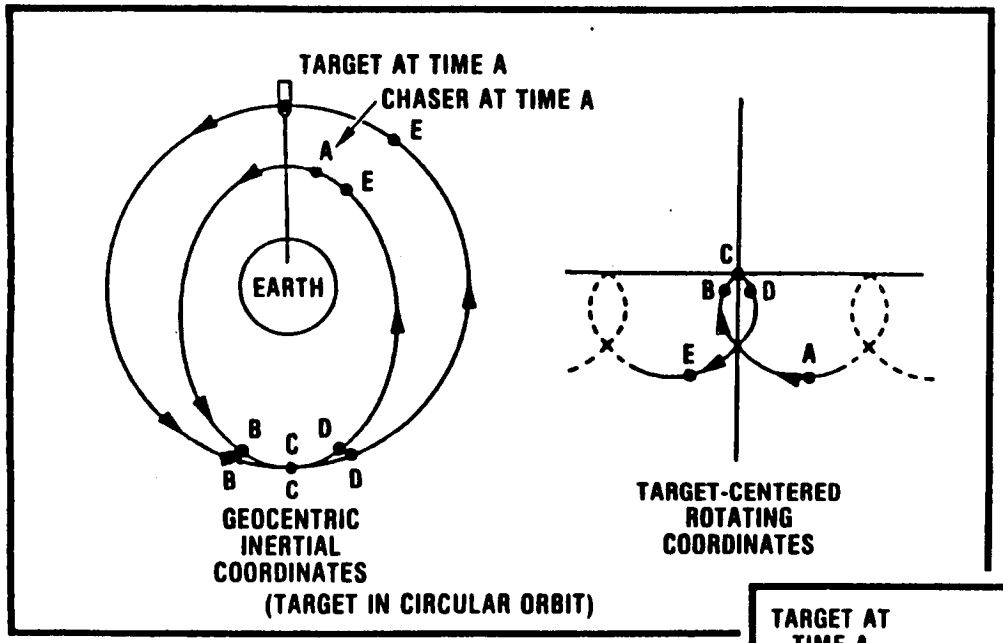


9-15

RENDEZVOUS PHASING ORBITS

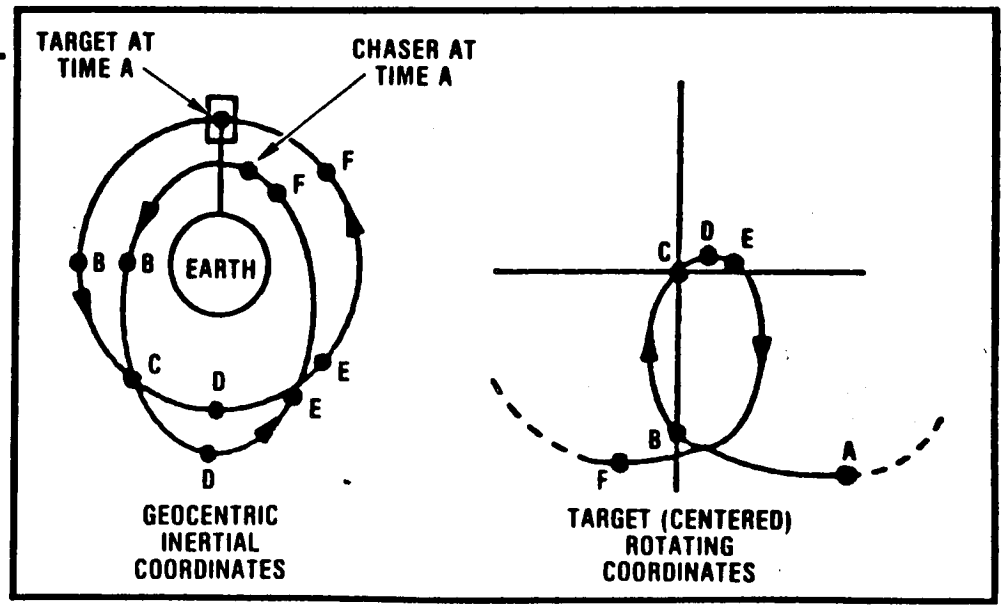
Rendezvous may be defined as the sequence of maneuvers designed to bring two vehicles into close proximity. These maneuvers start with the launch of the chase vehicle which achieves the desired orbit plane and timing to provide desired visual lighting conditions at rendezvous. Subsequent maneuvers establish the chase vehicle and target vehicle in coaxial orbits (share a common line of apsides or maneuver line). Maneuvers adjust the phasing between the target and chase vehicles and perform height adjustments with the objective of bringing the chase vehicle in an orbit coelliptic with and slightly below the target's orbit. Additional corrective maneuvers are made as required to adjust the orbit plane, a terminal maneuver to intercept the target, and midcourse and braking maneuvers to match velocities and establish stationkeeping with the target. At this point the remaining maneuvers are called proximity operations which may include stationkeeping for a period of time, a fly-around inspection, and a close approach for berthing or docking. The method by which phasing orbits are used to bring the chase vehicle into the vicinity of the target is illustrated in the two diagrams.

RENDEZVOUS PHASING ORBITS



TANGENTIAL ORBITS

INTERSECTING ORBITS

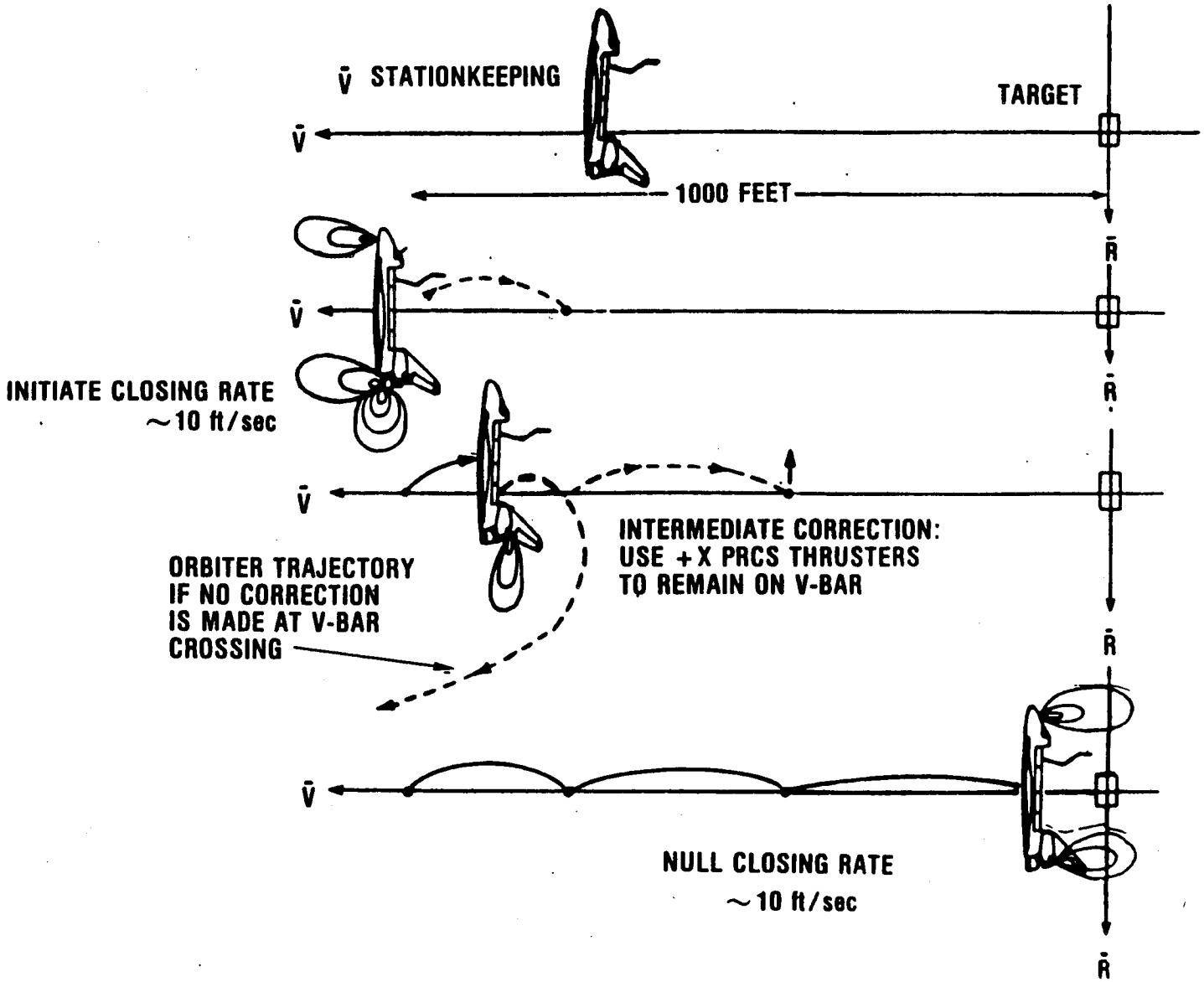


V-BAR STATIONKEEPING AND APPROACH

Proximity operations may be accomplished by a V-bar maneuver which derives its name from the relative motion axis system used to define positions of the target and chase vehicle. The axis system origin is established at the target vehicle and is a rotating LVLH reference frame. The horizontal axis is in the direction of flight, V-bar, and the vertical axis points toward the center of the earth, R-bar.

Typical V-bar stationkeeping and approach maneuvers for a satellite orbiter are illustrated.

V-BAR STATIONKEEPING AND APPROACH



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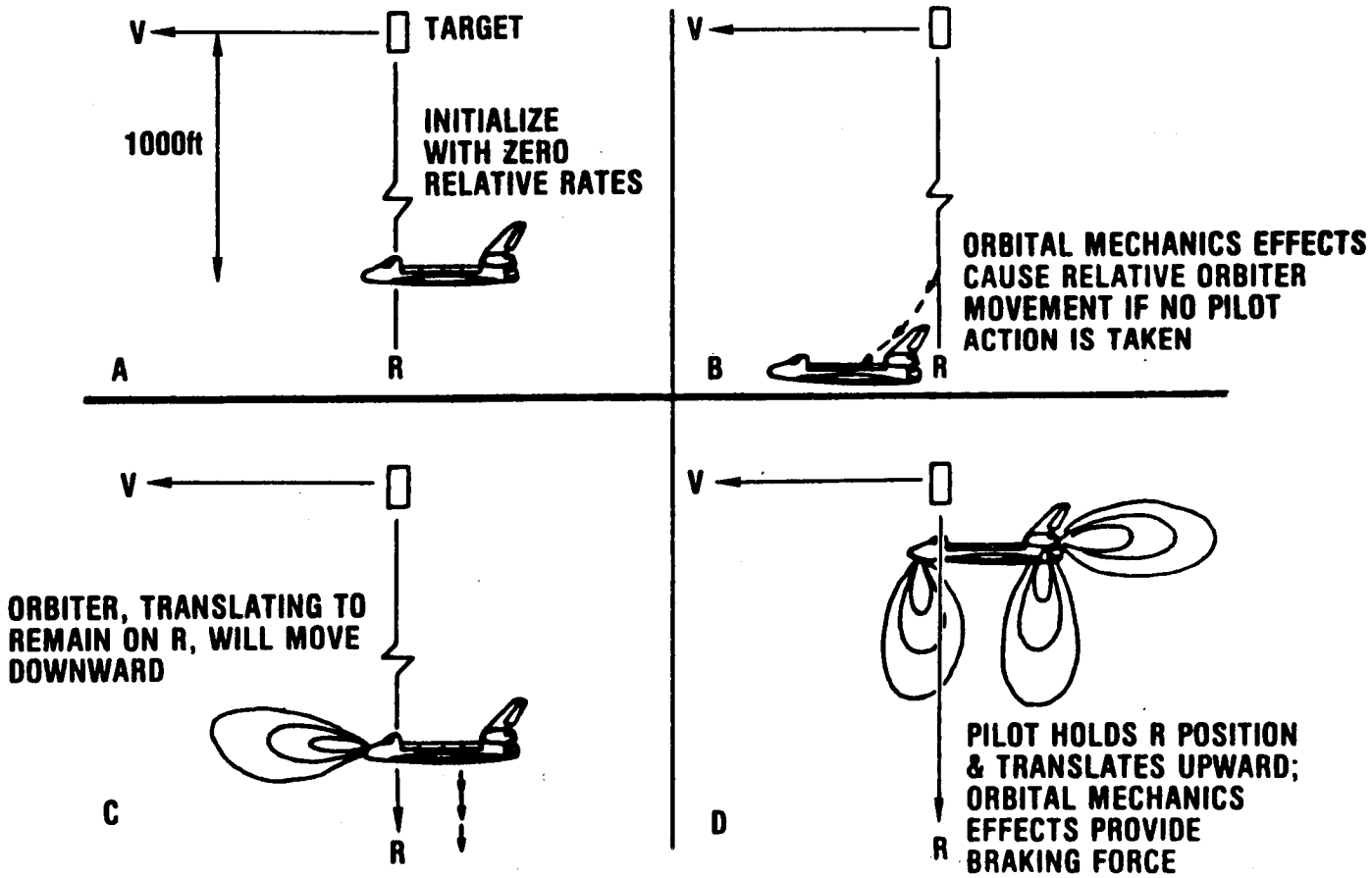
6-19

R-BAR APPROACH

The R-Bar approach method uses maneuvers to approach the target from below along the R-bar axis. The type of approach maneuver selected depends on propellant budgets, plume impingement geometry, crew vision, lighting and time constraints. The R-bar approach has natural braking features due to orbital mechanics which may avoid undesirable plume impingement effects.

9-20

R-BAR APPROACH METHOD USES ORBITAL MECHANICS EFFECTS TO PROVIDE BRAKING



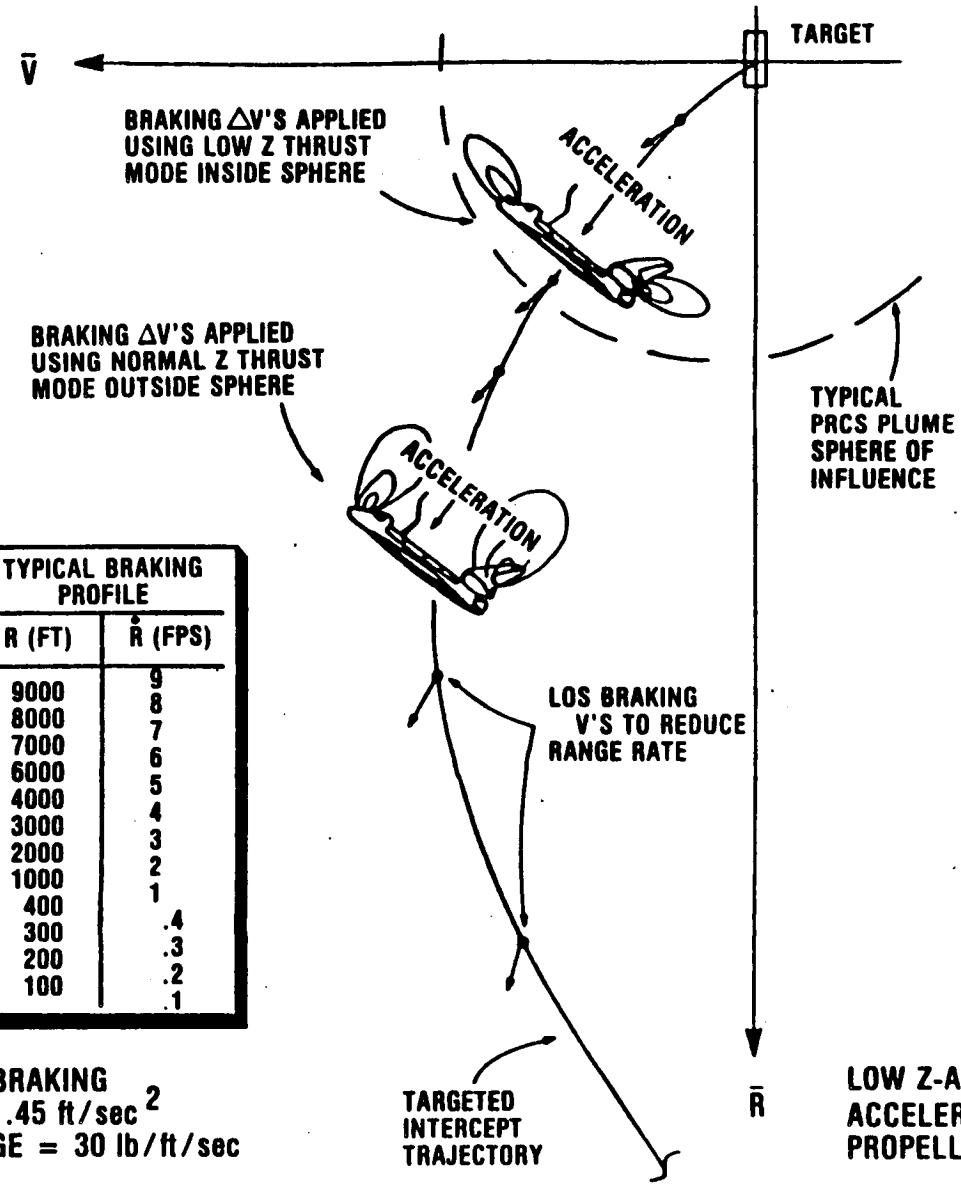
9-21

DIRECT APPROACH

A direct approach to the target presents advantages in timing and propellent consumption but may be detrimental because of braking maneuver thruster plume effects. The orbiter has a nominal Z-axis braking mode which is an efficient propellent mode but its use is constrained close to the target. A low Z-axis braking mode is more favorable for plume effects but is inefficient in it's propellent use.

9-22

CONTAMINATION REQUIRES RESTRICTIONS ON ORBITER CONTROL MODE DURING PROXIMITY OPERATIONS IN DIRECT APPROACH MODE



TYPICAL BRAKING PROFILE	
R (FT)	$\dot{R}$ (FPS)
9000	9
8000	8
7000	7
6000	6
4000	5
3000	4
2000	3
1000	2
400	1
300	.4
200	.3
100	.2
	.1

NOMINAL Z-AXIS BRAKING
ACCELERATION = .45 ft/sec^2
PROPELLANT USAGE = 30 lb/ft/sec

LOW Z-AXIS BRAKING
ACCELERATION = .05 ft/sec^2
PROPELLANT USAGE = 280 lb/ft/sec

9-23

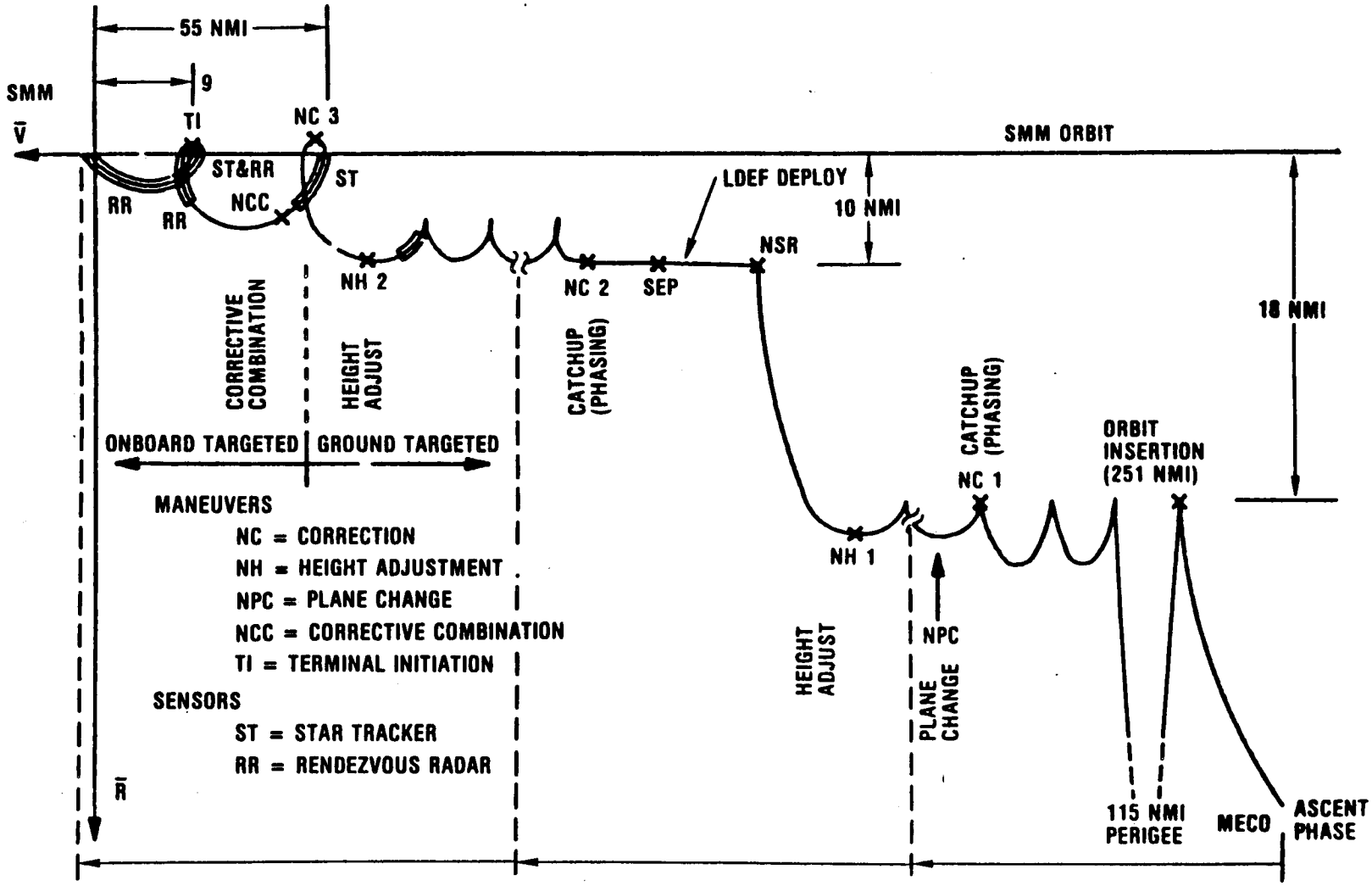
RENDEZVOUS PROFILE - SOLAR MAX MISSION STS-41C

The rendezvous profile of a recent Shuttle Orbiter mission, STS-41C, is illustrated. This mission featured the deployment of a LDEF satellite followed by rendezvous, retrieval, repair, and redeployment of the Solar Maximum Mission satellite.

Ground target maneuvers were executed until the orbiter could track the satellite with the star tracker. After approximately 55 nautical miles the maneuvers were targeted on board from star tracker data and later from rendezvous radar data (approximately the last 16 miles)

9-24

RENDEZVOUS PROFILE — SOLAR MAX MISSION STS-41C



9-25

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SOLAR MAX RENDEZVOUS PROFILE - PRIOR TO TI

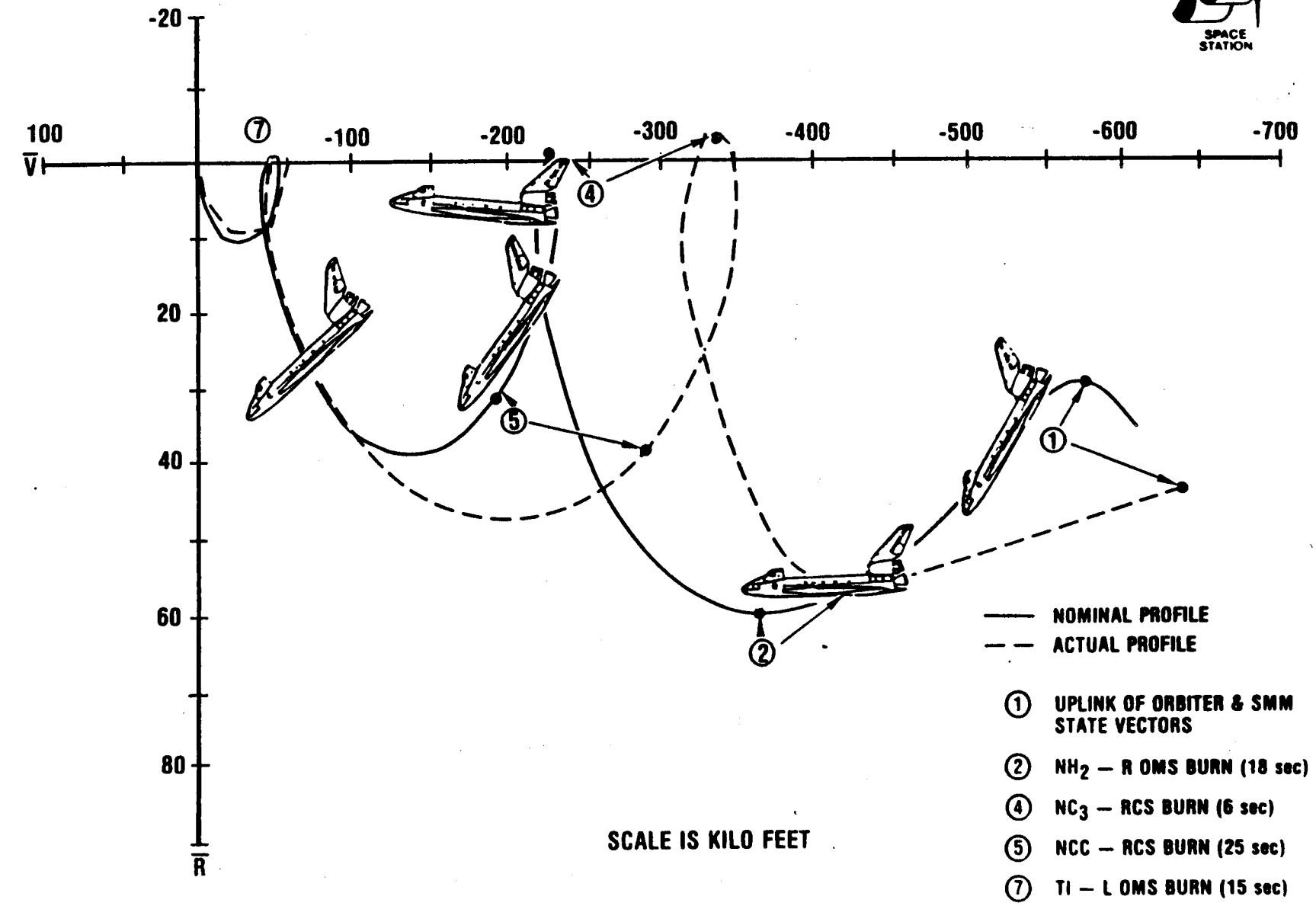
The nominal and actual trajectory profiles are compared for the maneuvers prior to the terminal initiation maneuver.

9-26

SOLAR MAX RENDEZVOUS PROFILE

(SMM AT CENTER OF ROTATING LVLH REFERENCE FRAME)

STS-41C



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9-27

SOLAR MAX RENDEZVOUS PROFILE - TI MANEUVER

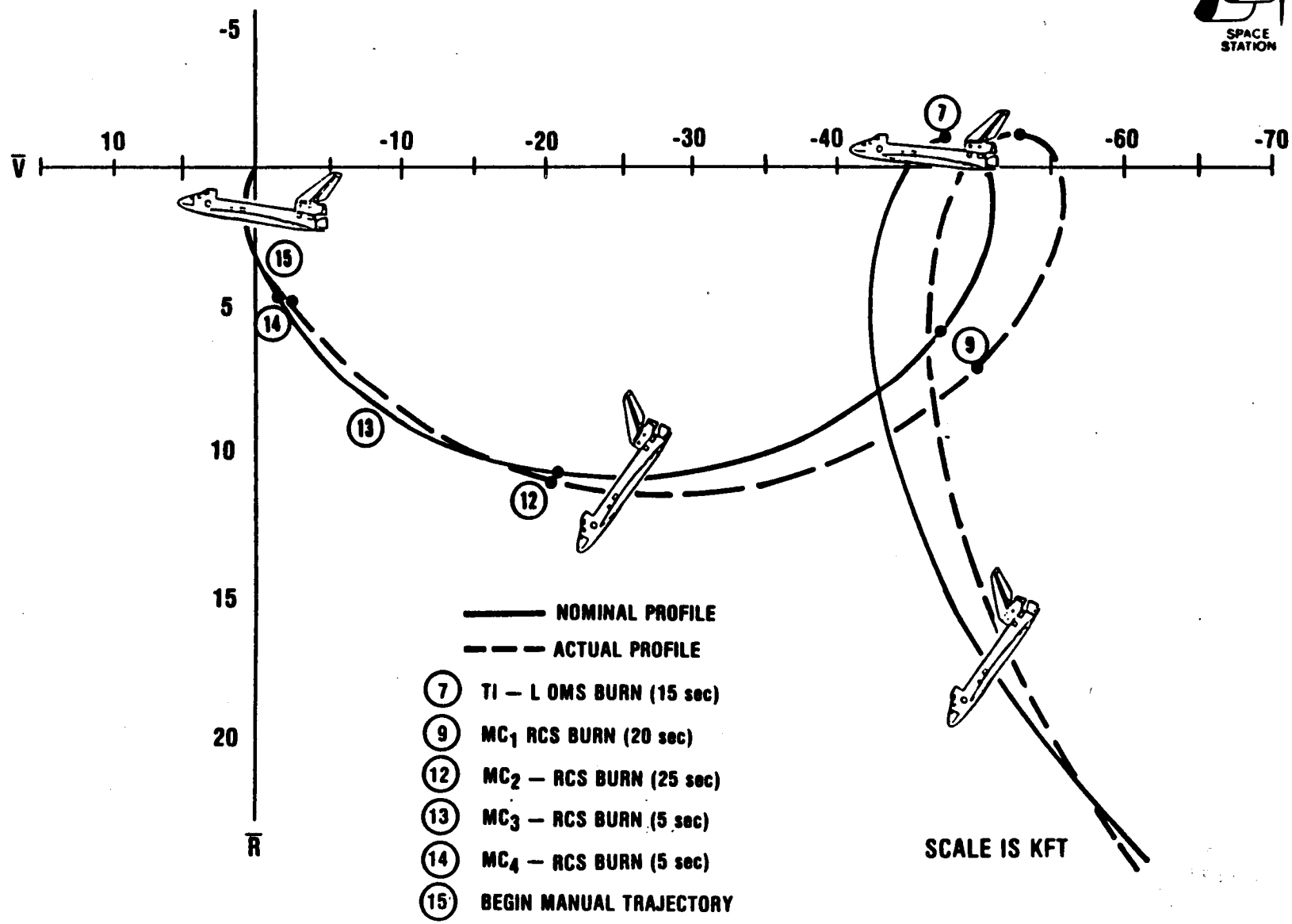
The terminal initiation burn in the actual profile was 11.7 ft/sec delta velocity, about twice what was originally planned. The four mid-course maneuvers brought the orbiter to the target satellite.

9-28

SOLAR MAX RENDEZVOUS PROFILE

(SMM AT CENTER OF ROTATING LVLH REFERENCE FRAME)

STS-41C



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9-29

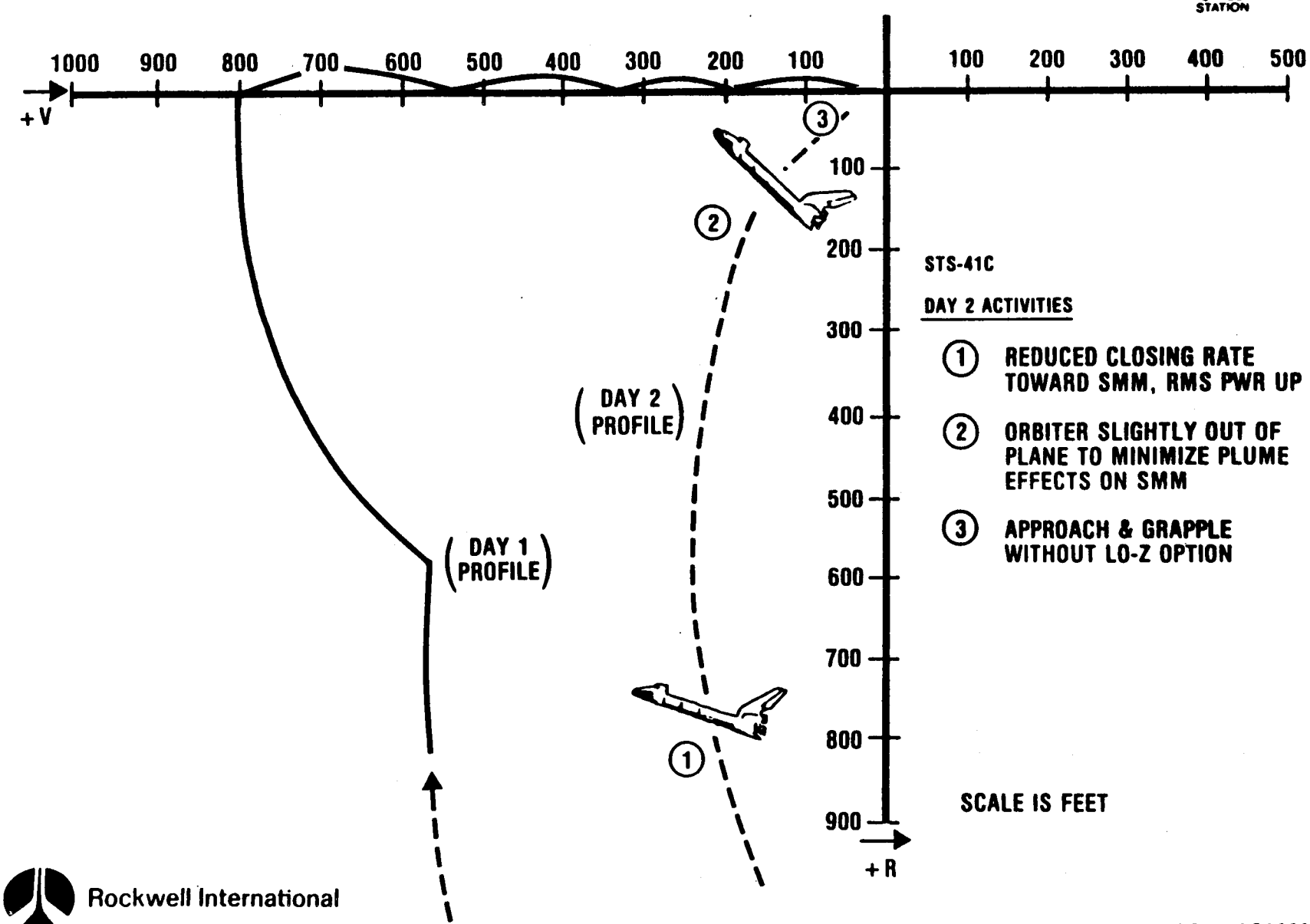
SOLAR MAX RENDEZVOUS PROFILE - APPROACH

Two approaches were made to the Solar Maximum Mission Satellite. The first attempt at grappling the satellite was unsuccessful. The orbiter set up stationkeeping and the second attempt was successful two days later. The proximity operations for the original approach was a typical V-bar approach. The second approach was a direct approach with the fuel efficient high Z mode used with plume effects minimized by an out-of-plane orientation. The second approach used 650 lbs less propellent than the first trajectory.

9-30

SOLAR MAX RENDEZVOUS PROFILE

(SMM AT CENTER OF ROTATING LVLH REFERENCE FRAME)



STS-41C

DAY 2 ACTIVITIES

1. REDUCED CLOSING RATE TOWARD SMM, RMS PWR UP
2. ORBITER SLIGHTLY OUT OF PLANE TO MINIMIZE PLUME EFFECTS ON SMM
3. APPROACH & GRAPPLE WITHOUT LO-Z OPTION

SCALE IS FEET

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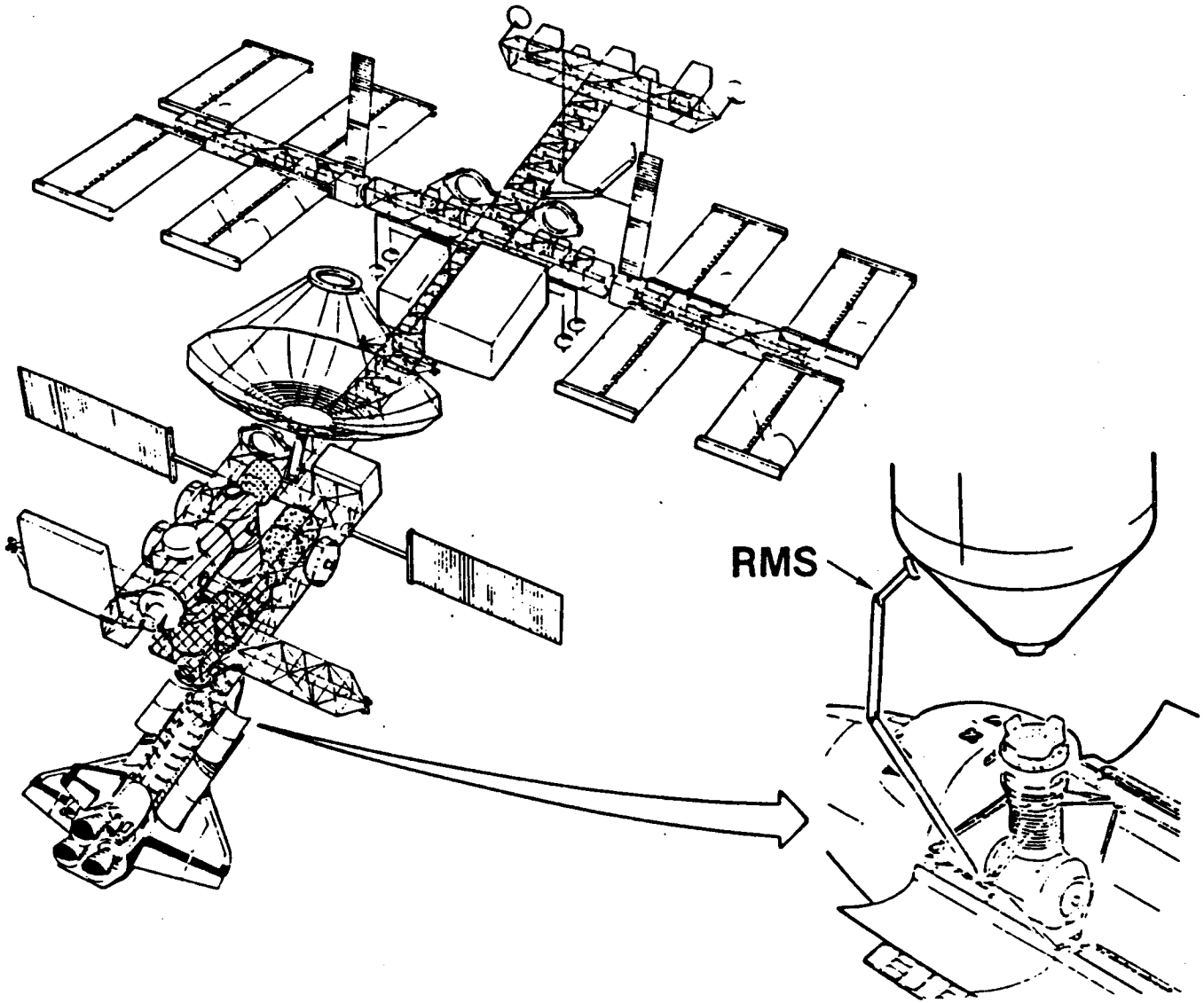
SHUTTLE ORBITER DOCKING/BERTHING INTERFACE

The docking of the Shuttle Orbiter to the Space Station is subject to trade studies to determine approach methods, control modes, berthing or docking methods, and the man/machine interface. Sensing requirements and visibility requirements are critical. The dynamics of the berthing/docking is complicated by the joining of two bodies of nearly equal mass at interfaces removed from their centers of mass.

SHUTTLE ORBITER DOCKING/BERTHING INTERFACE

SPACE STATION



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9-33

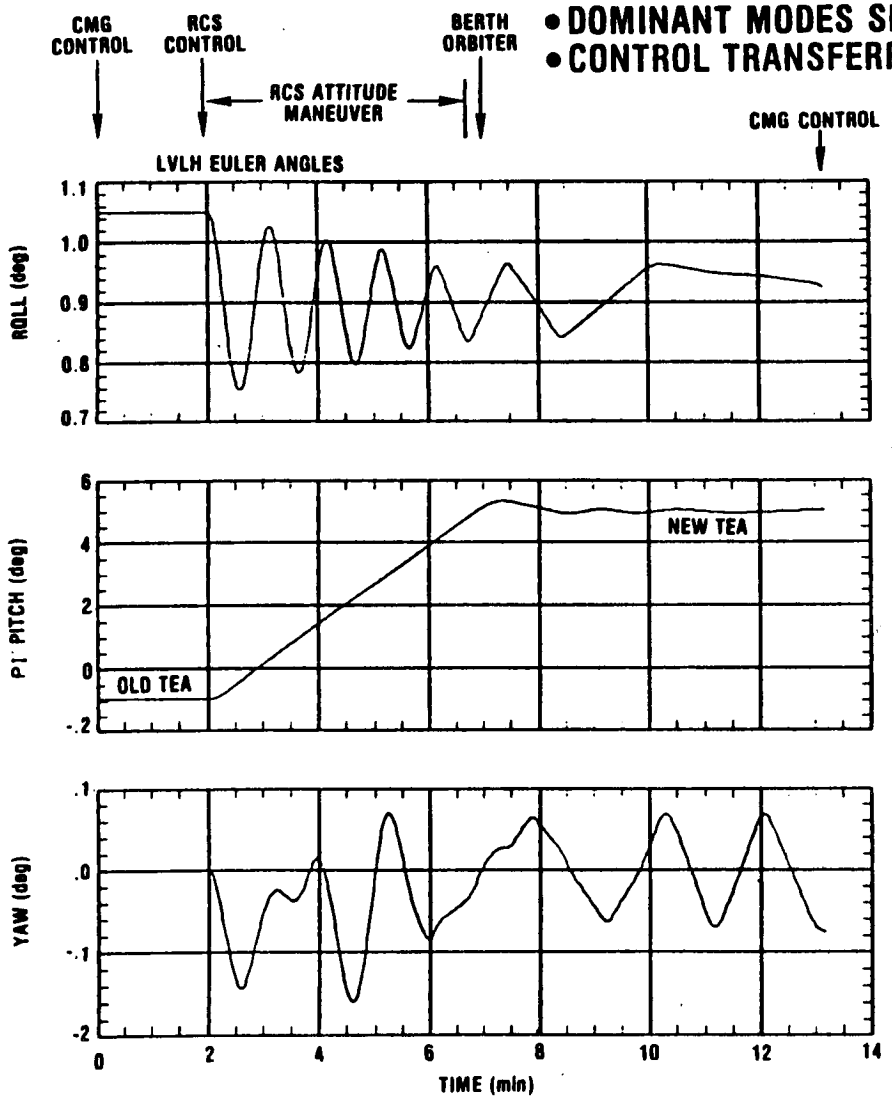
CONTROL OF BERTHING TRANSIENT IN FLEXIBLE STRUCTURE

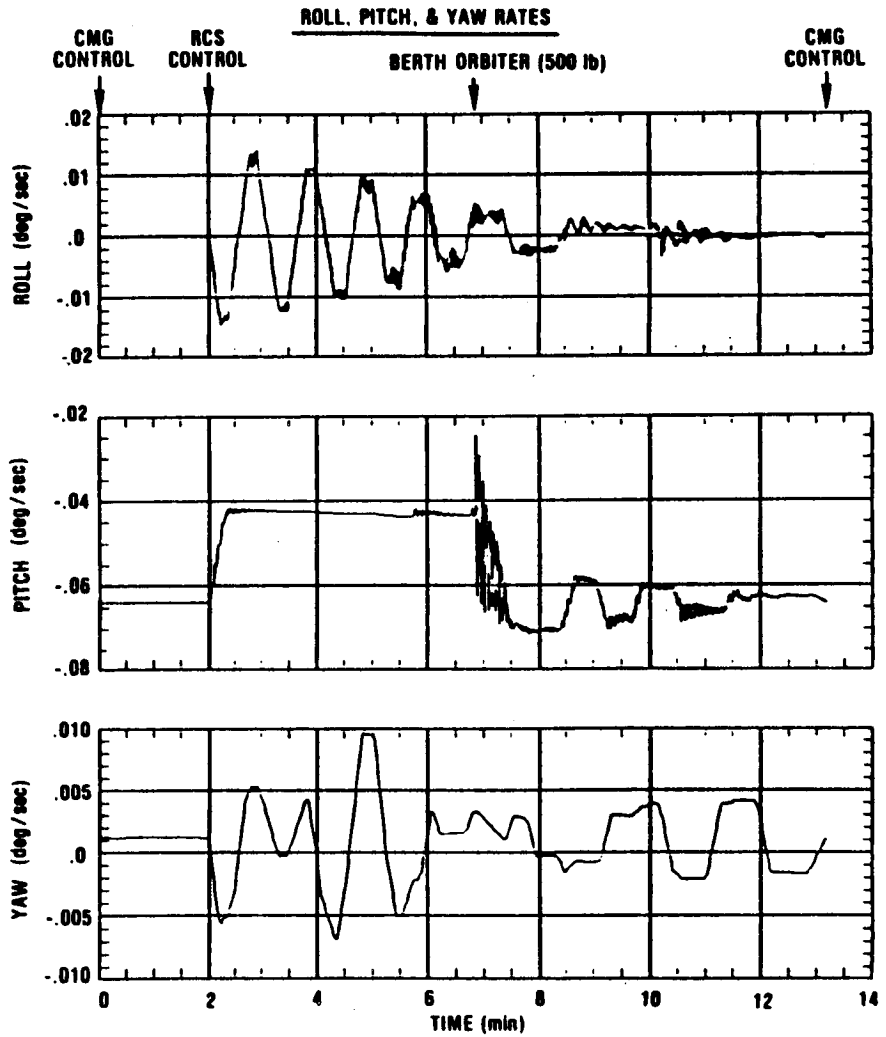
A possible scenario for the berthing of the orbiter to the space station is shown. Prior to the berthing the space station attitude is at the Torque Equilibrium Attitude (TEA). In this attitude the gravity gradient torques balance the drag induced torques over an orbit. With the shuttle orbiter attached the TEA is required to change value. The berthing sequence, in the scenario shown, starts with a takeover of control from the control moment gyros by the RCS system. The station is maneuvered to the new TEA before the orbiter approaches. The final orbiter approach is then followed by grappling and berthing. Control can then be transferred back to the CMG's.

9-34

CONTROL OF BERTHING TRANSIENT IN FLEXIBLE STRUCTURE

- GROWTH CONFIGURATION
- SIMULATION WITH NASTRAN FLEX MODEL
- DOMINANT MODES SELECTED BY MODAL GAIN ANALYSIS
- CONTROL TRANSFERRED TO RCS MODE FOR BERTHING





9-35

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EVOLUTION OF RENDEZVOUS OPERATIONS

The evolution of Rendezvous Operations in the areas of Guidance, Navigation and Control is depicted.

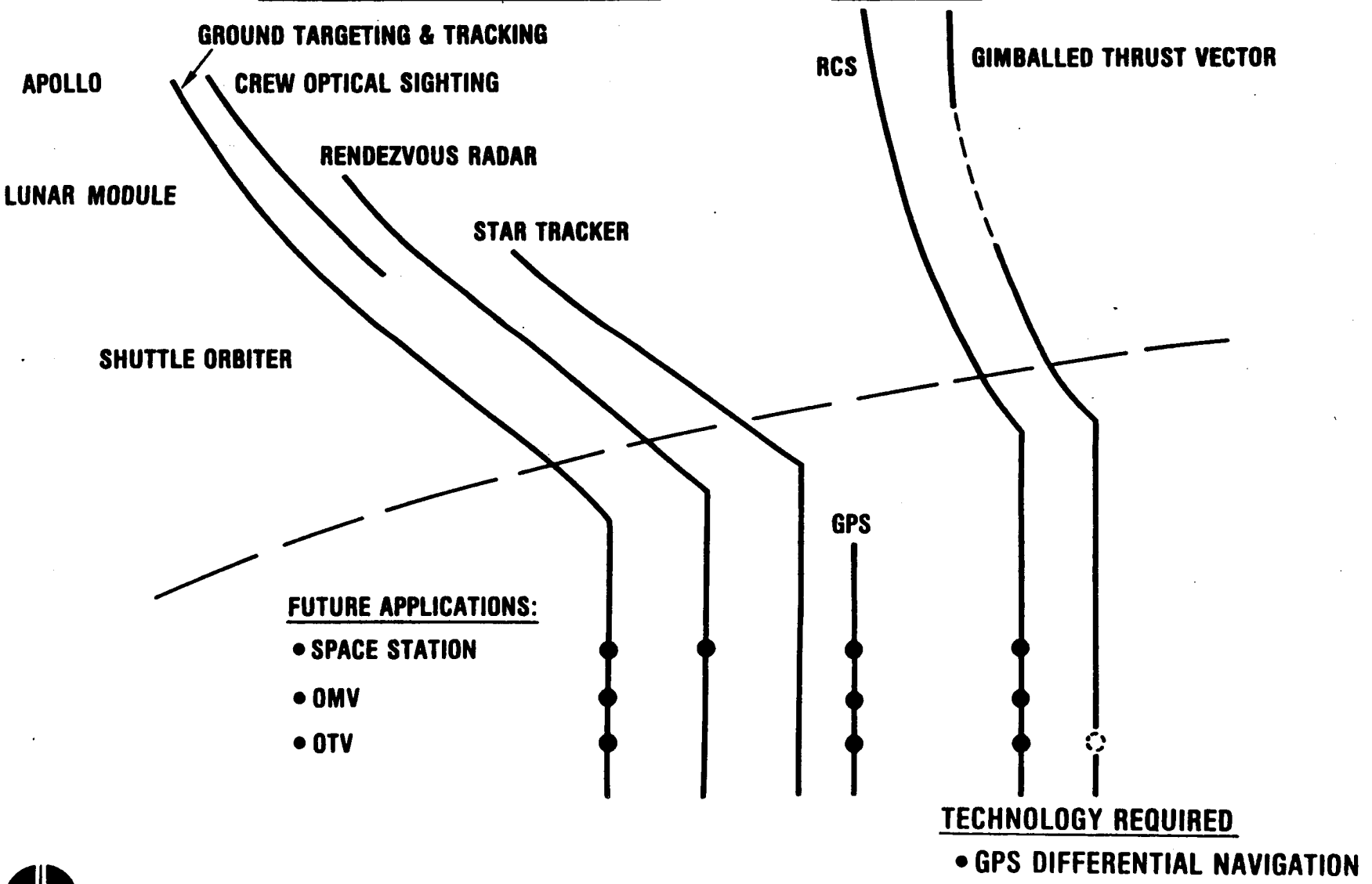
Guidance and Navigation maneuvers in the Apollo era and continuing into the Shuttle era have been dependent on ground targeting and tracking. The Apollo and Lunar Module (LM) used crew optical sighting and the LM based rendezvous radar for the critical rendezvous in lunar orbit. The shuttle orbiter uses a star tracker for far field sighting and rendezvous radar close-in. Optical sightings are available as backups.

Rendezvous operations with the Space Station will have available ground tracking and rendezvous radar, however, the use of GPS promises a more autonomous capability for relative navigation if both vehicles have GPS receivers.

Control for rendezvous maneuvers requires capability for attitude maneuvers for viewing, sighting, and propulsion maneuvers. Reaction Control System (RCS) jets provide attitude control moments. Rendezvous propulsive force is provided by an orbit maneuver propulsion which in the case of the Apollo and Shuttle is gimballed for control. The LM ascent stage utilized the RCS for control moments.

9-36

EVOLUTION OF RENDEZVOUS OPERATIONS



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EVOLUTION OF PROXIMITY OPERATIONS

The evolution of Proximity operations in the areas of Guidance, Navigation and Control is depicted.

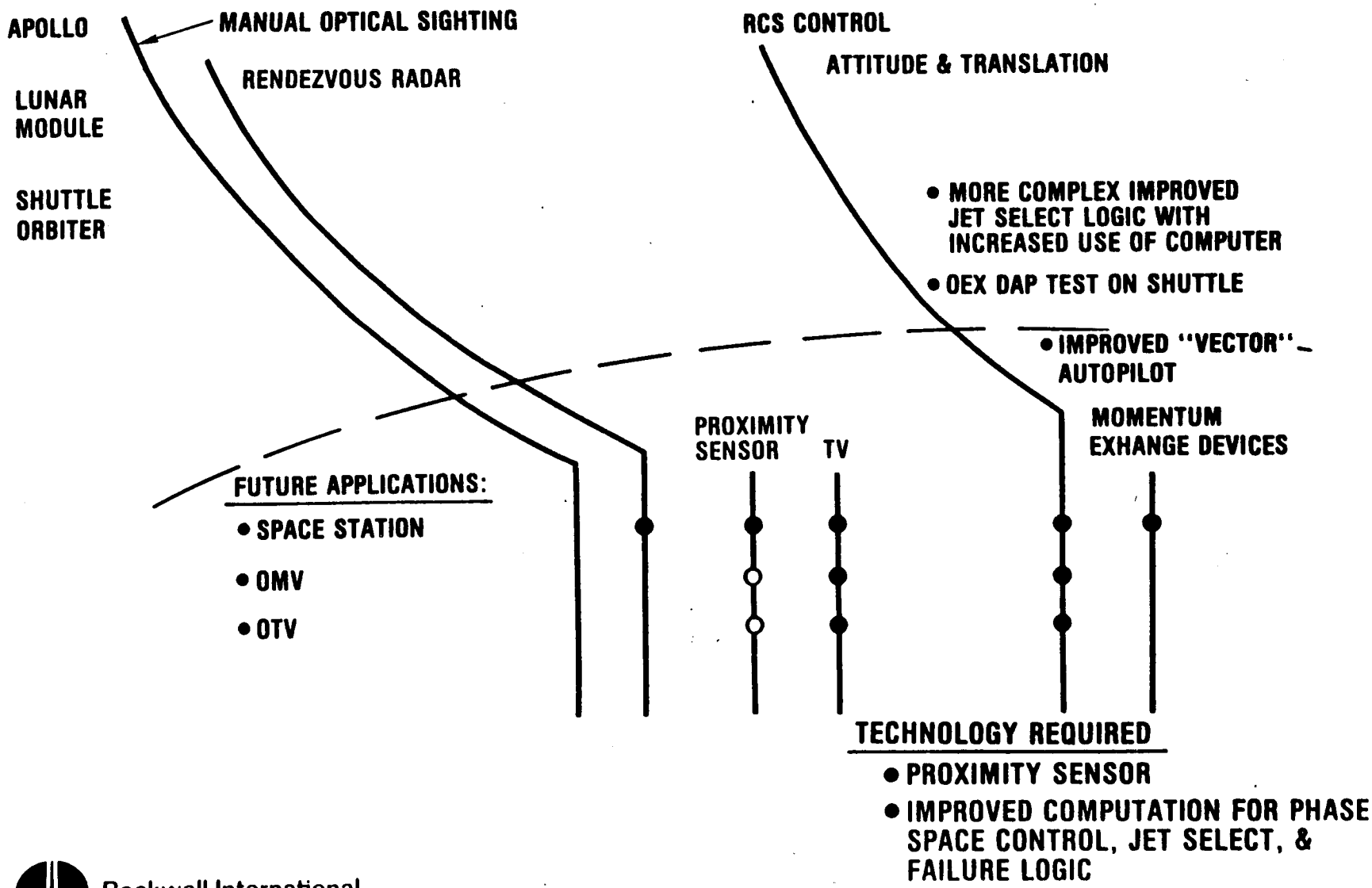
Guidance and Navigation targeting for Apollo were performed with a sextant. The Lunar Module added a Rendezvous Radar and the CSM had a cooperative transponder. The Shuttle Orbiter used both optical (Crewman Optical Alignment Sight (COAS)) and rendezvous radar observations.

The Space Station will build on this current technology adding potential requirements for a close-in proximity sensor and remote TV monitors. The Space Station will interface with orbiter, OMV, OTV and Space Platforms. The primary mode of operation of the OMV is a TV monitor with remote control from a control center either in the Space Station or on the ground.

Control is required during proximity operations for attitude maneuvers and control of translational maneuvers. The Shuttle attitude and translation control have been augmented by more complex improved jet select logic with increasing automation. The Experimental OEX digital autopilot is an upcoming Shuttle flight experiment. The Space Station will incorporate Control Moment Gyros for control in addition to RCS. Future advances are required in improved autopilot computations for phase space computations, jet select logic, and failure logic.

9-38

EVOLUTION OF PROXIMITY OPERATIONS



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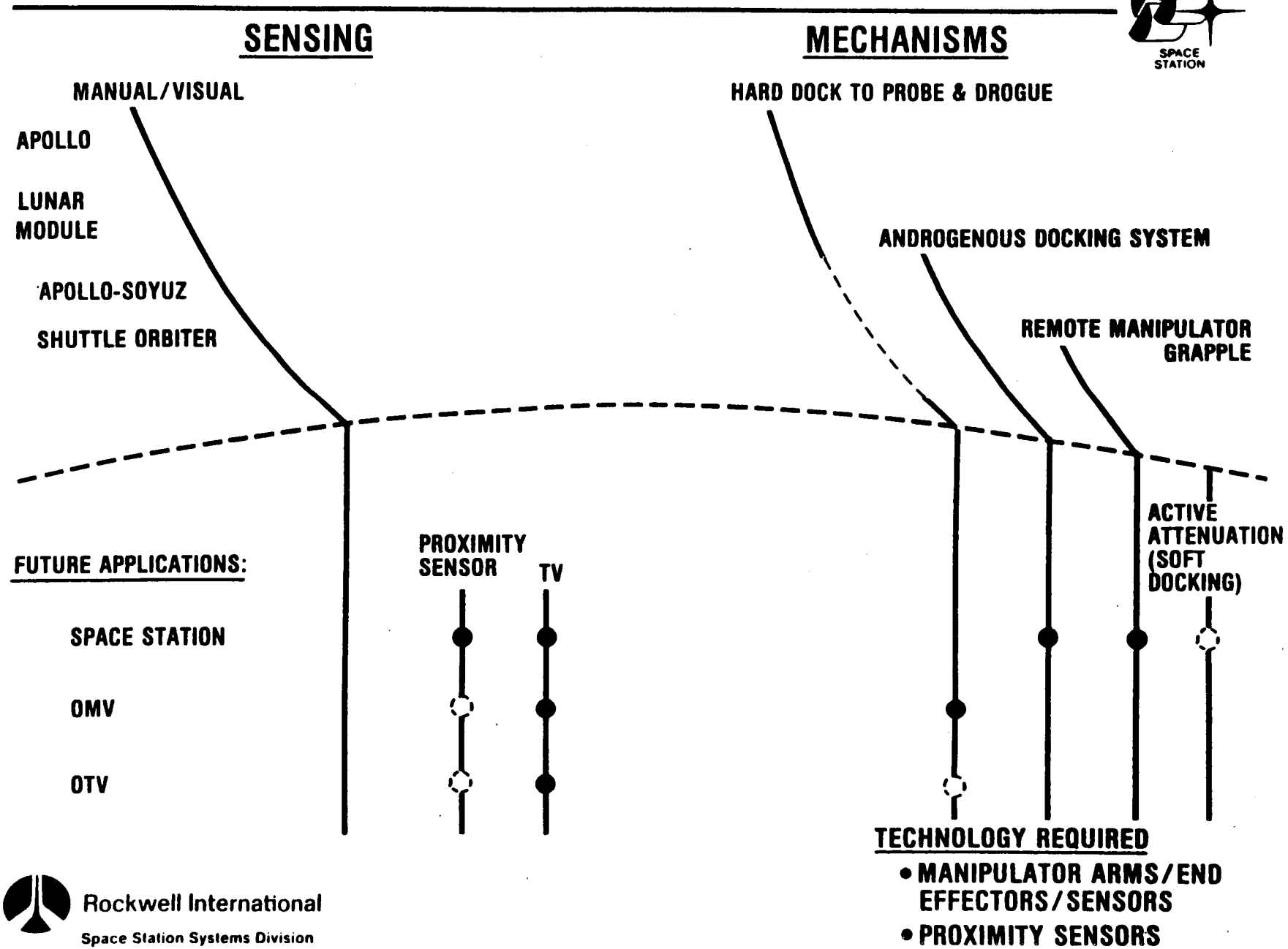
EVOLUTION OF SPACECRAFT JOINING (DOCKING/BERTHING)

The evolution of the techniques for joining of spacecraft is depicted.

The Apollo and Lunar Module joining was accomplished by a direct docking. Sensing of the docking operation was by visual observation of the target. A probe and drogue mechanism was used for docking. The Apollo Soyuz docking used an androgenous docking system, still with manual/visual sensing. The Shuttle Orbiter has introduced the use of a remote manipulator to grapple satellites.

Future operations in the space station will possibly use all these methods. Sensing will be augmented with a proximity sensor and remote TV monitors eventually developing automated docking or berthing operations. Technology advances are required in the proximity sensors and manipulator devices.

EVOLUTION OF SPACECRAFT JOINING (DOCKING/BERTHING)



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14-6

OVERVIEW

SPACE STATION

- MISSION PHASES
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- CONCLUSIONS & RECOMMENDATIONS

9-42

BASIC GN&C FUNCTIONAL REQUIREMENTS

The basic generic functions required for Rendezvous and Proxops are given in the chart, and were derived for the mission phases presented in an earlier chart.

BASIC GN&C FUNCTIONAL REQUIREMENTS

SPACE STATION

- GUIDANCE & NAVIGATION
  - RELATIVE TO EARTH
  - RELATIVE TO ANOTHER S/C
- NAVIGATION SENSING
- ATTITUDE CONTROL
  - ABSOLUTE
  - RELATIVE
- TRANSLATIONAL CONTROL
  - ONE DIMENSIONAL
  - THREE DIMENSIONAL

9-44

TYPICAL VEHICLES & SPACE OPERATIONS REQUIRING RENDEZVOUS AND PROXIMITY OPERATIONS

The chart identifies some of the vehicles and operations that are envisioned in current mission scenarios as requiring rendezvous and proximity operations.

9-45

TYPICAL VEHICLES AND SPACE OPERATIONS REQUIRING RENDEZVOUS AND PROXOPS

SPACE STATION

POTENTIAL VEHICLES

- SHUTTLE ORBITER(S)
- SPACE STATION
- ORBITAL MANEUVERING VEHICLE
- ORBITAL TRANSFER VEHICLE
- UNMANNED SPACE PLATFORM
- UNMANNED SPACECRAFT

OPERATIONS REQUIRING PROXOPS

- CONSTRUCTION/ASSEMBLY
- SERVICING/RESUPPLY
- RETRIEVAL
- RESCUE
- REPAIR
- STATIONKEEPING

9-46

OVERVIEW

SPACE STATION

- MISSION PHASES
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- CONCLUSIONS & RECOMMENDATIONS

SOME PROXOPS DESIGN ISSUES

Based on the generic mission phases, functional requirements, potential vehicles, and operations identified above, a series of design issues have been identified and are presented in the chart. These issues may be viewed as questions that should receive some consideration by the mission/system designers. Further elaboration on the more pertinent issues will be provided in subsequent charts.

Plume impingement is of concern due to its contaminating influences on payloads, potential changes in the thermal properties of surfaces, and the physical forces that can severely complicate or preclude successful proxops. The problem can be ameliorated through use of special thruster arrangements (inefficient) or through use of the special relative motion flight paths that employ orbital mechanics effects for braking, rather than propulsion. These factors plus many others influence the choice of relative motion approach trajectories. Although it is not apparent that these problems have been explored extensively, and clear answers obtained, the problems are well within the capabilities of many NASA agencies and industrial firms, and special technology development funding is not required. Similarly, the development of stationkeeping and formation flying techniques is thought to be well within current capability.

The level-of-automation and degree of crew involvement in the R & P operations, is a difficult design issue that has not always been decided on an objective basis in the past. However, objective bases for this type of design decision making do exist (such as minimization of life-cycle costs), and it is expected that the better engineering organizations can accomplish this within normal Phase B study constraints.

Un-identified object collision avoidance is listed due to its potential impact in the area of on-board tracking sensor requirements, and maneuvering propulsion requirements. It is clear that ground based tracking is not totally adequate for this purpose in that objects of less than approximately eight inches characteristic dimension cannot be tracked. Onboard acquisition and tracking systems tasks are at least as difficult as those envisioned for various "star wars" applications, and are well beyond any near term S.O.A. The estimated probability of these collisions for the manned vehicles in low earth orbit is quite low. In light of these considerations, it is likely that we will ignore these hazards, at least for the near future.

The choice of relative motion sensing technique(s) is an interesting one since many new options are potentially available in the near future (such as laser proxops sensors). This will be discussed further in subsequent charts.

CONTINUED ON THE BACK OF THE NEXT CHART

SOME PROXOPS DESIGN ISSUES (CONT'D)

The propulsion and control technology required for three axis translation and rotational control of maneuvering vehicles poses many design challenges, and these will also be discussed in subsequent charts.

The issue of direct docking versus manipulator grappling and berthing is also pertinent. For the large ungainly vehicles whose designs are compromised by mission functions other than proxops (such as the orbiter), where crew safety is involved, and manipulator equipment is partially amortized through the performance of other functions, the use of manipulators seems appropriate. The two stage operation of grappling and berthing can certainly improve safety. On the other hand, for small low-cost unmanned vehicles, there are probably situations in which direct docking would be the most cost effective approach. It is concluded that both techniques will probably be required, the choice depending on the specific situation. The remote manipulator system utility is so high in future mission scenarios that its technology will be discussed in a subsequent chart.

The operation of an unmanned maneuvering vehicle in the proximity of a manned spacecraft imposes new safety issues that have not arisen in the past. These issues require thorough exploration, but should not require special technology development.

The facility requirements to accommodate tumbling spacecraft can be quite imposing in terms of mass and cost. These costs must be traded with the potential savings in being able to rescue the tumbling spacecraft, and against the costs of redundancy within the tumbling spacecraft so that it can damp its own tumbling. A remote manipulator with robust performance can accommodate low-rate tumbling by itself. The use of the manipulator for other unplanned operations argues for the achievement of robust dynamic performance in the manipulator.

SOME PROXOPS DESIGN ISSUES

SPACE STATION

- PLUME IMPINGEMENT, CONTAMINATION, & AVOIDANCE
- SAFETY — COLLISION AVOIDANCE
- RELATIVE MOTION TRAJECTORIES
- STATIONKEEPING/FORMATION FLYING TECHNIQUES
- DEGREE-OF-AUTOMATION & CREW INVOLVEMENT
- UNIDENTIFIED OBJECT COLLISION AVOIDANCE
- RELATIVE MOTION NAVIGATION SENSING
- THREE DIMENSIONAL TRANSLATION & ATTITUDE CONTROL
- PROPULSION TECHNOLOGY ADVANCEMENTS NEEDED
- DIRECT DOCK vs MANIPULATOR GRAPPLE & BERTH
- ACTIVE MANEUVERING OF UNMANNED VEHICLE IN PROXIMITY OF MANNED VEHICLE
- ACCOMMODATION OF TUMBLING/NON-COOPERATIVE SPACECRAFT
- CONTROLLER ALGORITHM DESIGN & ANALYSIS TECHNOLOGY

9-50

OVERVIEW

SPACE STATION

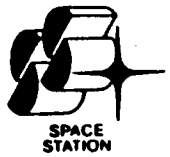
- MISSION PHASES
- HISTORICAL EVOLUTION OF RENDEZVOUS/ PROXOPS CAPABILITIES
- GENERIC FUNCTIONAL REQUIREMENTS
- DESIGN ISSUES
- TECHNOLOGY OPTIONS
- POTENTIAL TECHNOLOGY DEVELOPMENT CANDIDATES
- CONCLUSIONS & RECOMMENDATIONS

9-51

CANDIDATE APPROACH TRAJECTORIES

Numerous relative motion trajectories for the R&P approach to the target vehicle have been investigated in the literature, and several of these have been flight tested. The more significant issues for emphasis are listed in the chart. Four out of the five profiles illustrated there possess desirable features regarding plume impingement and "thrust-failed-off" collision avoidance. Although there is no evidence in the literature that an intensive analysis and trade study has been performed to define the best techniques for the near future space operations, it is felt that this analysis is straightforward, and no special technology development activity is thought to be needed.

CANDIDATE APPROACH TRAJECTORIES



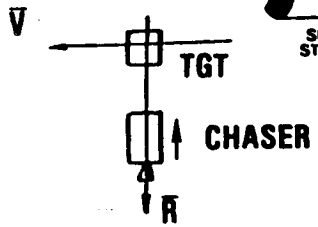
EMPHASIS:

- PLUME IMPINGEMENT AVOIDANCE
- FAIL-SAFE COLLISION AVOIDANCE
- GUIDANCE ERROR SENSITIVITY
- PROPELLANT CONSUMPTION

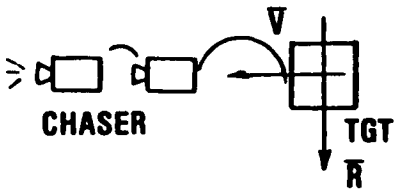
CONCLUSION:

- TRAJECTORIES WITH "ORBITAL MECHANICS" BRAKING OFFER ADVANTAGES IN PLUME AVOIDANCE & THRUST-OFF FAILURE COLLISION AVOIDANCE

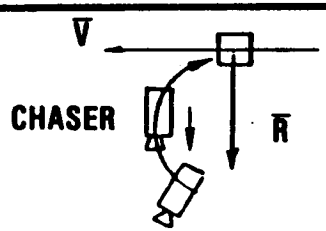
- $\bar{R}$ APPROACH



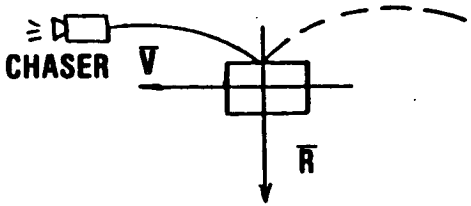
- $\bar{V}$ APPROACH



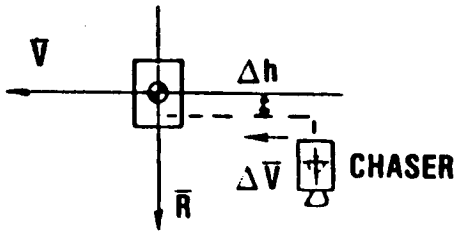
- DIRECT APPROACH



- "ONE-IMPULSE"



- Δh DRIFT



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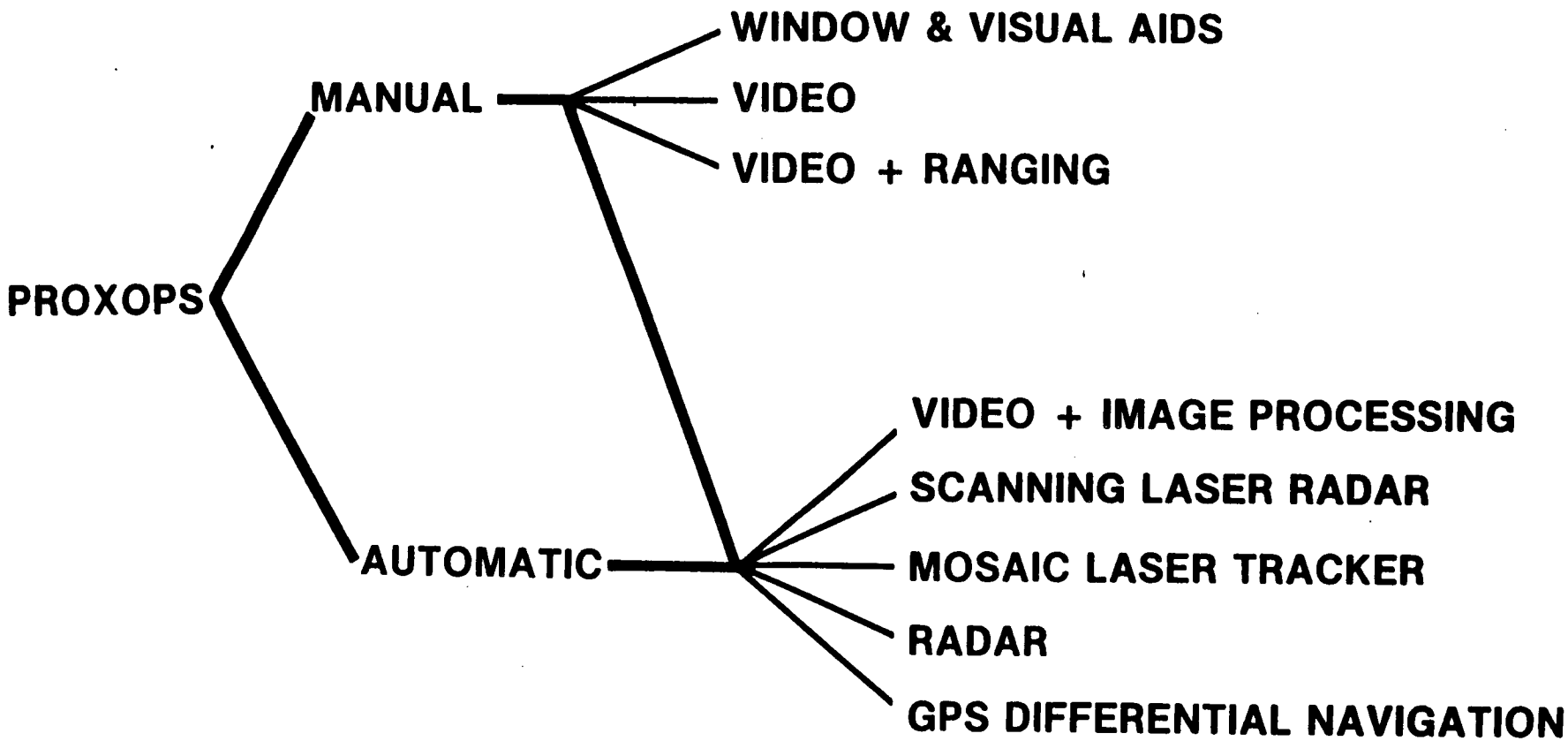
9-53

RELATIVE MOTION SENSING CANDIDATES

The chart gives a listing of some of the relative motion navigation sensors that might be considered. The tree separates the candidates that utilize crew observations (and hence are more appropriate for manual control) from the automated sensor observations that are applicable to more highly automated operations. The highly repetitive proxops envisioned in the Space Station era may warrant the use of more highly automated control of these operations relative to earlier space operations. In such a scenario the loss of crew time and the costs of extensive crew training in the proxops control area may well outweigh the cost of developing the more highly automated system.

9-54

RELATIVE MOTION SENSING CANDIDATES



9-55

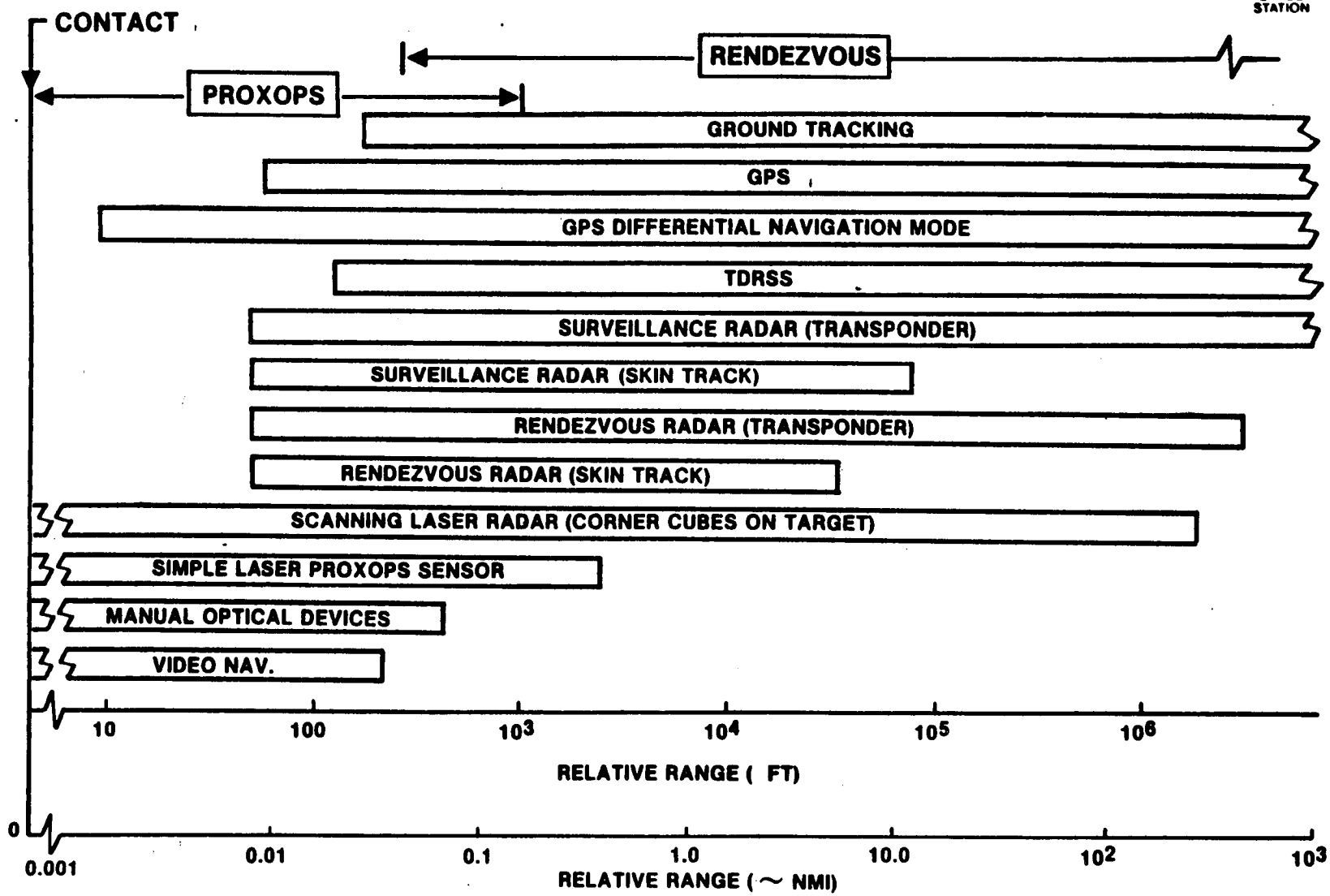
RELATIVE MOTION SENSOR--RANGE OF APPLICATION

The ranges at which the candidate relative motion navigation sensors will function is given in the chart. The GPS Differential Navigation mode is capable of providing the most accurate navigation data in the rendezvous phase, and can operate down to very short range. Many of the vehicles under consideration may utilize GPS for orbital navigation, in which case,the relative motion navigation sensing function can be derived almost for free. This low cost navigation approach can potentially alleviate the requirement for a more expensive rendezvous radar.

Among the sensors that are capable of operating down to contact conditions, a laser based sensor is probably the most attractive candidate from the standpoint of high accuracy, sensitivity to solar interference, and modest cost. The merits of such a proxops sensor are described in a subsequent chart.

9-56

RELATIVE MOTION SENSORS — RANGE OF APPLICATION



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9-57

OVERVIEW

SPACE STATION

- MISSION PHASES
- HISTORICAL EVOLUTION OF RENDEZVOUS/ PROXOPS CAPABILITIES
- GENERIC FUNCTIONAL REQUIREMENTS
- DESIGN ISSUES
- TECHNOLOGY OPTIONS
- POTENTIAL TECHNOLOGY DEVELOPMENT CANDIDATES
- CONCLUSIONS & RECOMMENDATIONS

9-58

GPS DIFFERENTIAL NAVIGATION

One promising new technique for deriving very accurate relative motion data for use in control of R & P flight phases is illustrated in the chart. Relative motion navigation accuracies in the range of 1 to 3 meters is possible through some simple extensions in the navigation filter. The pseudo-range signals from the target vehicle are relayed to the chaser vehicle and processed together with its own pseudo-range data. In this fashion the dominant systematic biases are essentially subtracted out, resulting in accuracies that are much improved over the normal GPS earth-relative navigation data. The GPS Differential Navigation approach is described in numerous references, including "The Application of NAVSTAR Differential GPS in the Civilian Community", Jacques Beser and Bradford W. Parkinson, Intermetrics Inc. paper.

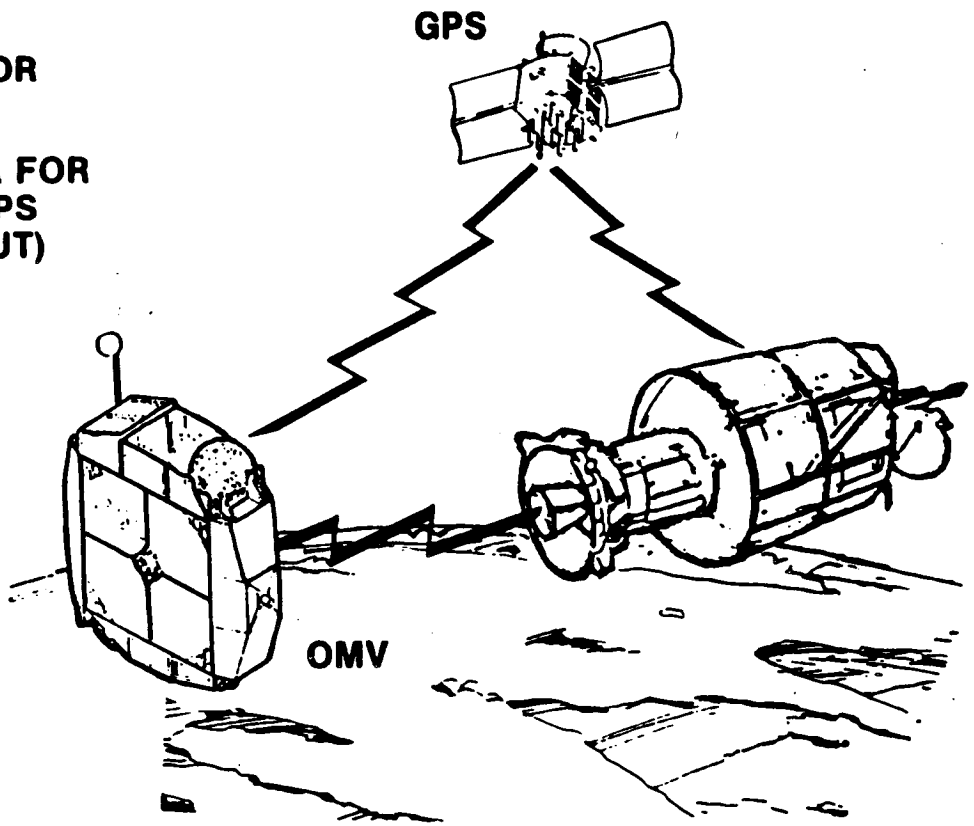
The technique is potentially capable of eliminating the need for a rendezvous radar and is capable of operating down to very short relative ranges. The use of other augmenting signals, such as relative range data, also offer promise. This concept is not reccommended for advanced technology development funding since the analysis is well within the capability of existing agencies and firms during normal Phase B studies, and the GPS receiver hardware is already under development.

9-59

GPS DIFFERENTIAL NAVIGATION

SPACE STATION

- **PROCEDURE**
  - PROCESS GPS DATA NORMALLY FOR EARTH RELATIVE NAVIGATION
  - DIFFERENCE PSEUDO RANGE DATA FOR RELATIVE MOTION NAVIGATION (GPS SYSTEMATIC BIASES SUBTRACT OUT)
- **ACCURACIES**
  - EARTH RELATIVE — <50M
  - S/C RELATIVE — <1-3M
- **REQUIREMENTS — GPS RECEIVERS & DATA LINK**



PROVIDES LOW COST RELATIVE MOTION NAVIGATION DATA FOR COOPERATIVE SPACECRAFT WITH GPS RECEIVERS

9-60

PROXIMITY OPERATIONS GUIDANCE SENSOR

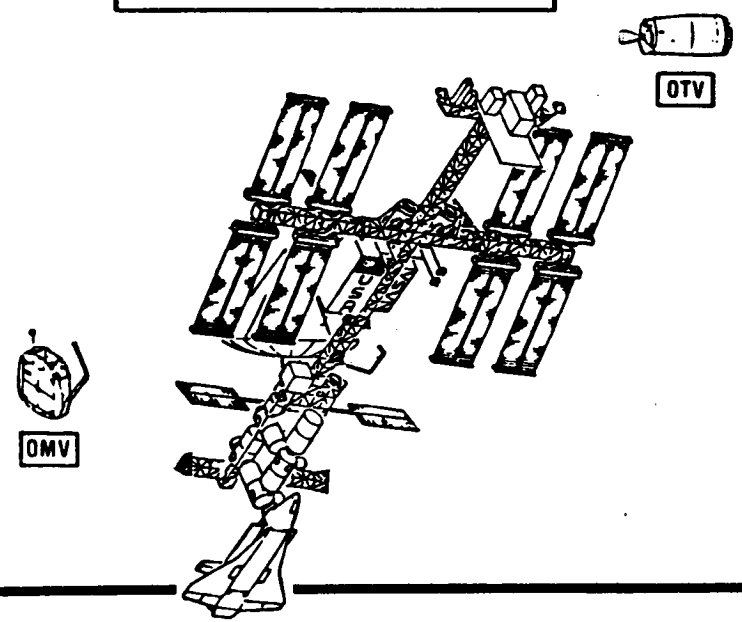
The advances in the electro-optical technology now make it possible to achieve highly accurate proxops sensors that are capable of providing the sensing needed for automatic guidance and control through contact or grappling. The approach offers large improvement in: contact mechanism requirements, maneuvering propellant reduction, operational safety and reliability relative to the manual sensing and control methods previously employed. Although the cost effectiveness of the automatic approach has probably not been proven rigorously, it is thought that the cost of crew training and the related ground support over the long life-cycle envisioned for Space Station and OMV type vehicles, will exceed those of a more automated system that employs the crew for failure monitoring.

PROXIMITY OPERATIONS GUIDANCE SENSOR

SPACE STATION

PROBLEM — NO DEVELOPED SENSOR SYSTEM DIRECTLY APPLICABLE TO AUTOMATED CONTROL OF PROXOPS CURRENTLY EXISTS

PROPOSED CONCEPT



ELECTRO-OPTICAL SENSORS (LASER BASED) OFFER MANY ADVANTAGES FOR PROXOPS CONTROL:

- ELIMINATES NEED FOR RENDEZVOUS RADAR
- HIGH ACCURACY FROM RADAR RANGES DOWN TO CONTRACT CONDITIONS
- AUTOMATED PROXOPS WILL IMPROVE ACCURACIES (REDUCE CONTACT MECHANISM REQUIREMENTS), REDUCE PROPELLANT CONSUMPTION, IMPROVE OPERATIONAL RELIABILITY & SAFETY, & REDUCE COSTS (MAJOR REDUCTION IN CREW TRAINING)

TECHNOLOGY DEVELOPMENT NEEDS?

- SYSTEM ENGINEERING & TRADE STUDIES TO DEFINE PREFERRED SYSTEMS & SENSOR COMPONENTS
- PROXOPS SENSOR DESIGN, LABORATORY, & FLIGHT DEMONSTRATION

9-62

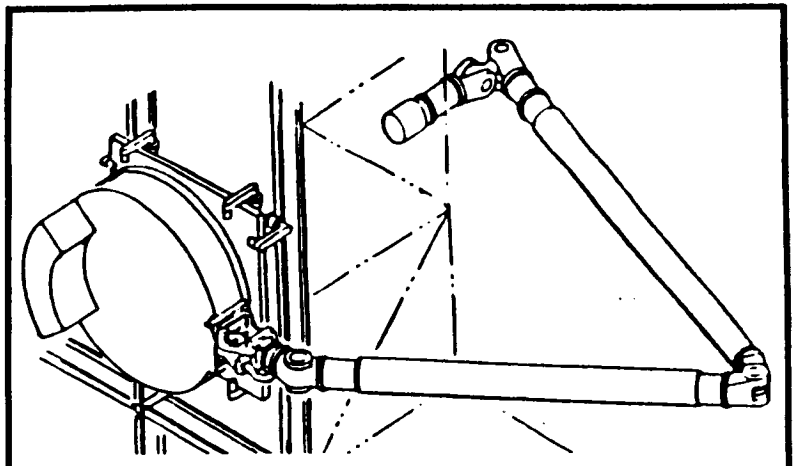
REMOTE MANIPULATOR SYSTEM ADVANCES

The Shuttle RMS has vividly proven the utility of such devices in spaceborne operations. However, many advances and design improvements have occurred in this technology since the orbiter RMS was conceived and designed. The high utilization of these devices projected for the Space Station era warrants the use of these technology advances. It is recommended that the technology development in this area be enhanced relative to current levels, and that the scope of the targeted applications be expanded to include the Space Station, OMV, and an advanced system for the Shuttle.

9-63

REMOTE MANIPULATOR SYSTEM ADVANCES

SPACE STATION



REMOTE MANIPULATOR SYSTEM

STATUS

- SHUTTLE RMS OPs HAVE DEMONSTRATED UTILITY
- HIGH UTILIZATION IN FUTURE SPACE OPS WARRANT SUBSTANTIAL ADVANCES
- ADVANCES IN COMPONENT (BUILDING-BLOCK) TECHNOLOGY NOW PERMIT LARGE IMPROVEMENTS
- CAN CAPTURE MUCH MORE DIFFICULT OPERATIONS & REDUCE NEED FOR EVA

POTENTIAL ADVANCE/IMPROVEMENTS — IMPROVED ACCURACY, AGILITY, DEXTERITY, SPEED-OF-RESPONSE, & ROBUST STABILITY VIA:

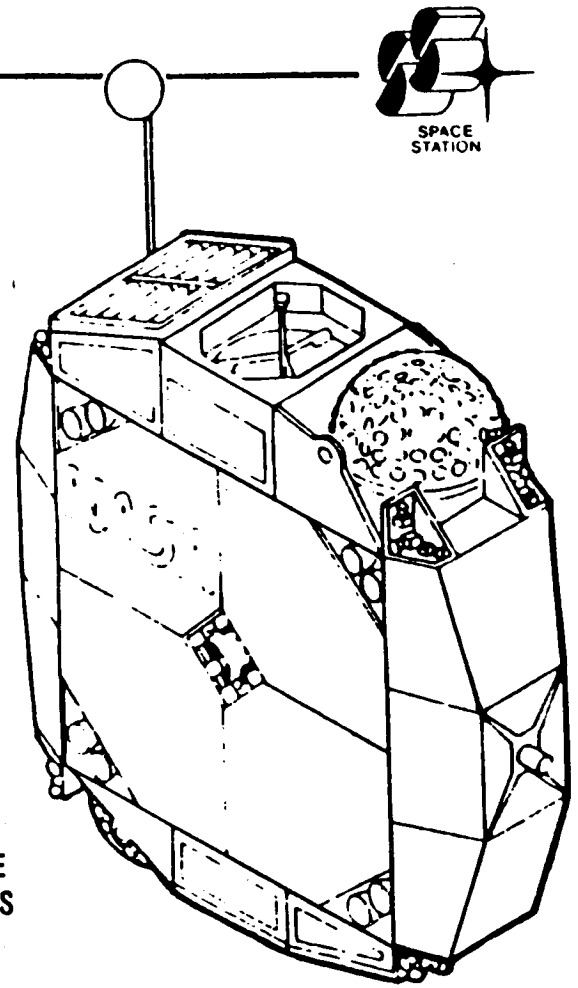
- END-EFFECTORS — BETTER DEXTERITY, TACTILE SENSING & FEEDBACK (SOFTER TOUCH), & MORE USEFUL, MULTI-FUNCTION END-EFFECTORS
- TELEPRESENCE & POSITION SENSING — NEW SMALL CCD CAMERAS PERMIT CLOSER INTEGRATION INTO END-EFFECTORS; & DIGITAL IMAGE PROCESSING FOR POSITION, STABILIZATION, & HOMING DATA
- INTEGRATED LASER PROXOPS SENSOR
- ROBUST COLLISION AVOIDANCE
- IMPROVED DYNAMIC CONTROL — ADAPTIVE, PREDICTIVE, & LEARNING CONTROL; END-EFFECTOR SENSING (CO-LOCATED)

REACTION JET CONTROL OF TRANSLATION AND ATTITUDE MANEUVERING

Chemical propulsion is the principal means that current technology has provided for translational control during Proxops, and no other method for accomplishing this is on the horizon (with the possible exception of tethers). The simultaneous control of reaction jet thrusters for three dimensional translation and attitude control poses a challenging design problem, particularly when using some level of manual control with remote control transport lags in the command loop of up to several seconds. The current technology for the design and analysis of the non-linear on-off reaction jet controllers is certainly not as straight forward as for linear systems. However, the phase plane, describing function, and time domain simulation techniques are certainly adequate to do the job, and no major technology advances are felt to be required. The OEX Advanced Autopilot, scheduled for a future flight test in the Shuttle orbiter, is perceived to be a major advance in reaction jet controllers of this type.

9-65

REACTION JET CONTROL OF TRANSLATION AND ATTITUDE MANEUVERING



- POSSIBLE PROPULSION TECHNOLOGY NEEDS
  - DEEP THROTTLING
  - PULSE MODE DYNAMIC RANGE
  - MULTI-THRUST LEVELS
  - PROPELLANTS MINIMIZING CONTAMINATION
- REACTION JET CONTROL TECHNOLOGY NEEDS
  - THRUSTER CONFIGURATION GEOMETRY
    - CROSS-COUPLING
    - PLUME IMPINGEMENT
  - JET SELECT LOGIC
  - PULSE COMMAND LOGIC — QUASI-LINEAR PULSE WIDTH MODULATION; NON-LINEAR PHASE SPACE APPROACHES
- SOME ISSUES
  - FLEXIBLE STRUCTURE & SLOSH/CONTROL SYSTEM INTERACTION & STABILITY
  - MINIMIZE TRANSLATIONAL & ROTATIONAL CROSS COUPLING
  - ROBUST PERFORMANCE IN PRESENCE OF CONFIGURATION, MASS, & CENTER-OF-MASS CHANGES

9-66

OVERVIEW

- MISSION PHASES
- HISTORICAL EVOLUTION OF RENDEZVOUS/ PROXOPS CAPABILITIES
- GENERIC FUNCTIONAL REQUIREMENTS
- DESIGN ISSUES
- TECHNOLOGY OPTIONS
- POTENTIAL TECHNOLOGY DEVELOPMENT CANDIDATES
- CONCLUSIONS & RECOMMENDATIONS

MULTI-DISCIPLINARY AND MULTI-PROGRAM ASPECTS OF PROXOPS AND ORGANIZING TO MEET THE CHALLENGE

R & P requires a broad variety of basic engineering disciplines. Virtually all of these basic disciplines are well understood. In broad engineering problems of this type, there is a proclivity for oversight because no centralized responsibility for coordinating the activities of the various engineering specialists is established. A guidance & control organization is an ideal one for performing this systems engineering function since virtually all these basic engineering disciplines are contained in the G&C function. In the present case the problem is further compounded because proxops generally involves more than one vehicle, each with a separate contractor, and in the process of procuring the hardware systems, it is easy to ignore the design of certain interface systems and operations.

It may be seen that there is a requirement for an organizational structure that can properly manage and integrate these multi-disciplinary, and multi-program participants, to obtain the proper design trades, interface requirements, and integrated operations.

MULTI-DISCIPLINARY AND MULTI-PROGRAM PROXOPS AND ASPECTS OF ORGANIZING TO MEET THE CHALLENGE

SPACE STATION

- PROXOPS REQUIRES BROAD DIVERSITY OF ENGINEERING DISCIPLINES (FLIGHT MECHANICS, SENSORS, GN&C SYSTEMS, CREW, ETC)

  - REQUIRES SYSTEMS ENGINEERING APPROACH

- BROAD DIVERSITY OF S/C USERS (SHUTTLE ORBITERS, OMVs, OTVs, SPACE STATION, SPACE PLATFORMS, UNMANNED SPACECRAFT, ETC)

  - REQUIRES ORGANIZED APPROACH ACROSS SPACECRAFT PROGRAMS

- POTENTIAL COST SAVINGS THROUGH STANDARDIZATION OF TECHNIQUES & EQUIPMENT

9-29

CONCLUSIONS AND RECOMMENDATIONS

The fundamental Rendezvous and Proximity (R & P) Operations technology building blocks are now much more mature, and better understood, than during the Apollo and Shuttle development phases. This is primarily due to more recent advances in onboard computer and distributed processing system technology, laser based electro-optical sensors, remote manipulator systems, and orbital navigation techniques such as the GPS. These advances now permit easier achievement of higher automation levels than was practical in prior programs, when warranted for more cost effective operations. The expanded scope and repetition of R & P operations during the Space Station suggests that a higher level of automation may be more cost-effective.

It is recognized that R & P operations require a broad diversity of basic engineering disciplines, and that a well organized "systems engineering" approach can avoid the "oversights" that sometimes occur in this situation. Also the multi-program/contractor nature of proxops requires a strong level of organization and integration across these programs.

Technology development work is underway in virtually all the areas defined as development candidates. However, several areas are recommended for enhanced funding, and for a broader application focus. The application focus should include the full family of potential user vehicles projected for near future space operations. These technology development areas are felt to offer a "highly leveraged return" for the investment.

RENDEZVOUS AND PROXIMITY OPERATIONS CONTROL OVERVIEW —
CONCLUSIONS & RECOMMENDATIONS

SPACE STATION

- BASIC PROXOPS TECHNOLOGY BUILDING BLOCKS ARE WELL UNDERSTOOD & ARE MUCH MORE MATURE THAN IN APOLLO & SHUTTLE DEVELOPMENT PHASES
- PROXOPS TECHNOLOGY STATUS NOW PERMITS MORE HIGHLY AUTOMATED SYSTEMS THAN EARLIER PROGRAMS WHEN NEEDED FOR COST EFFECTIVE OPERATIONS
- WORK IS UNDERWAY IN VIRTUALLY ALL AREAS OF TECHNOLOGY NEED, HOWEVER, FUNDING SCOPE & APPLICATION FOCUS COULD BE IMPROVED IN SOME AREAS
- NEED AN ORGANIZED APPROACH TO EFFICIENTLY INTEGRATE THESE TECHNOLOGIES WITHIN A PROGRAM & ACROSS DIFFERENT SPACECRAFT PROGRAMS
- POTENTIAL TECHNOLOGY DEVELOPMENT AREAS FOR ENHANCED FUNDING & BROADER APPLICATION FOCUS:
  - PROXOPS SENSOR
  - PROXOPS INTEGRATION
  - REMOTE MANIPULATORS

9-72

RCS ARCHITECTURAL ISSUES FOR SPACE VEHICLE RENDEZVOUS AND PROXIMITY OPERATIONS

Rendezvous and Proximity Operations Workshop

February 19-22, 1985

E. Bergmann
S. Croopnick
K. Daly

8501M304-1

HISTORICAL PERSPECTIVE

	Early Requirements	Current Requirements	Emerging Requirements
Attitude	Stabilize only; ~ few degrees	Open or closed loop; maneuver; ~ 1 deg	Closed loop maneuvers pointing << 1 deg
Fuel efficiency	Short missions; operational constraint	Significant planning impact	High premium for varied, long missions
Redundancy	Fail op/fail safe	Fail op/fail safe; software limited	High redundancy; long life/low maintenance
Configuration changes	None	Highly specific (e.g., Apollo dock)	Adaptability to growth; variety of configurations
Blending	None	None	Make best use of several effectors, e.g., CMG, jets, aero
Translation	Deorbit only	Orbit changes, open loop prox ops	Orbit trim, closed loop prox ops
Docking	None	Manual; open loop	Automatic, several types of targets
Flex	Rigid	Soft CSM/LM coupling	Significant elements may require damping
Autonomy	Low	Civil - low Military - high	High
Life	Several hours	~ weeks	~ years

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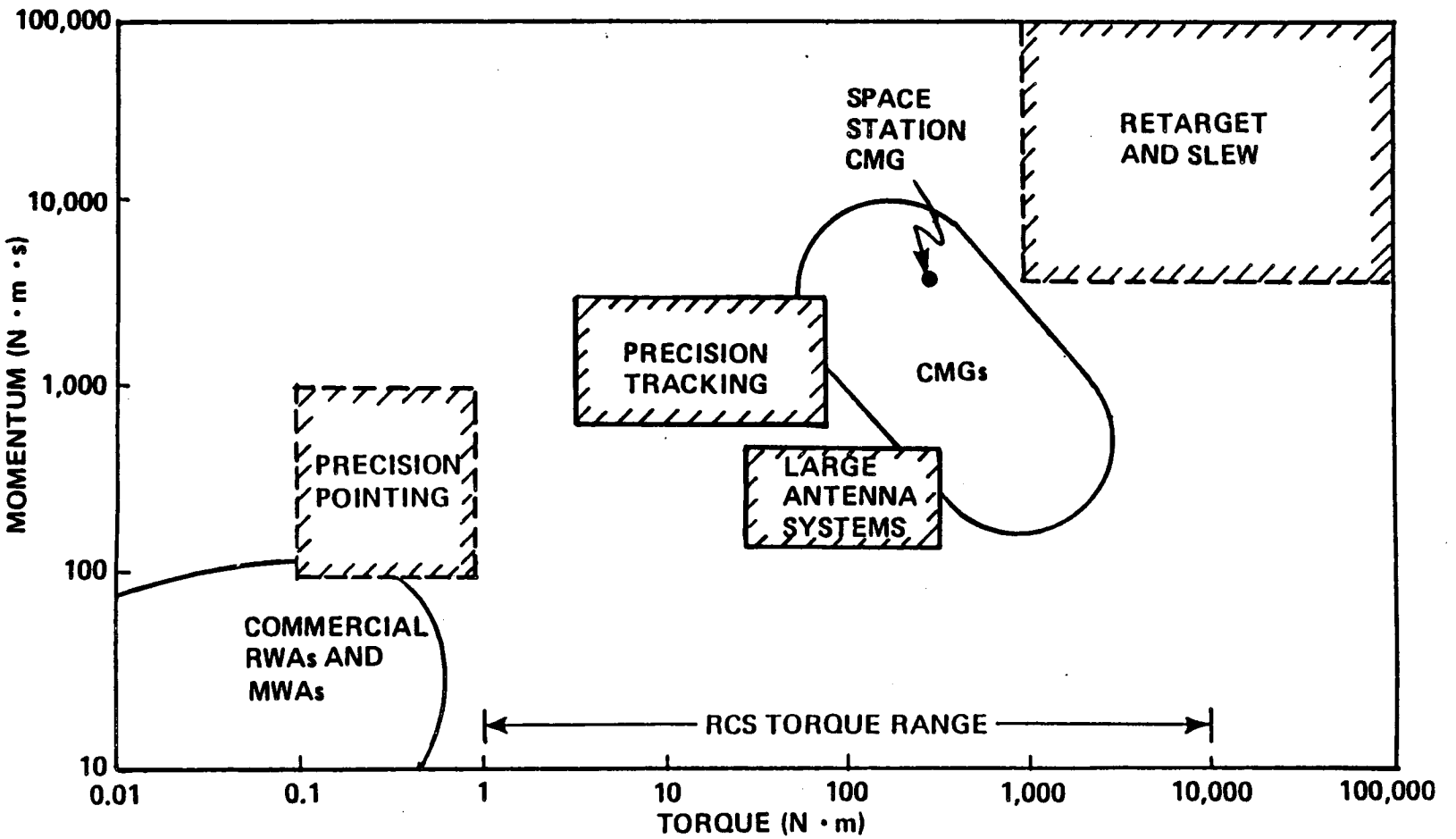
ACTUATOR REQUIREMENTS



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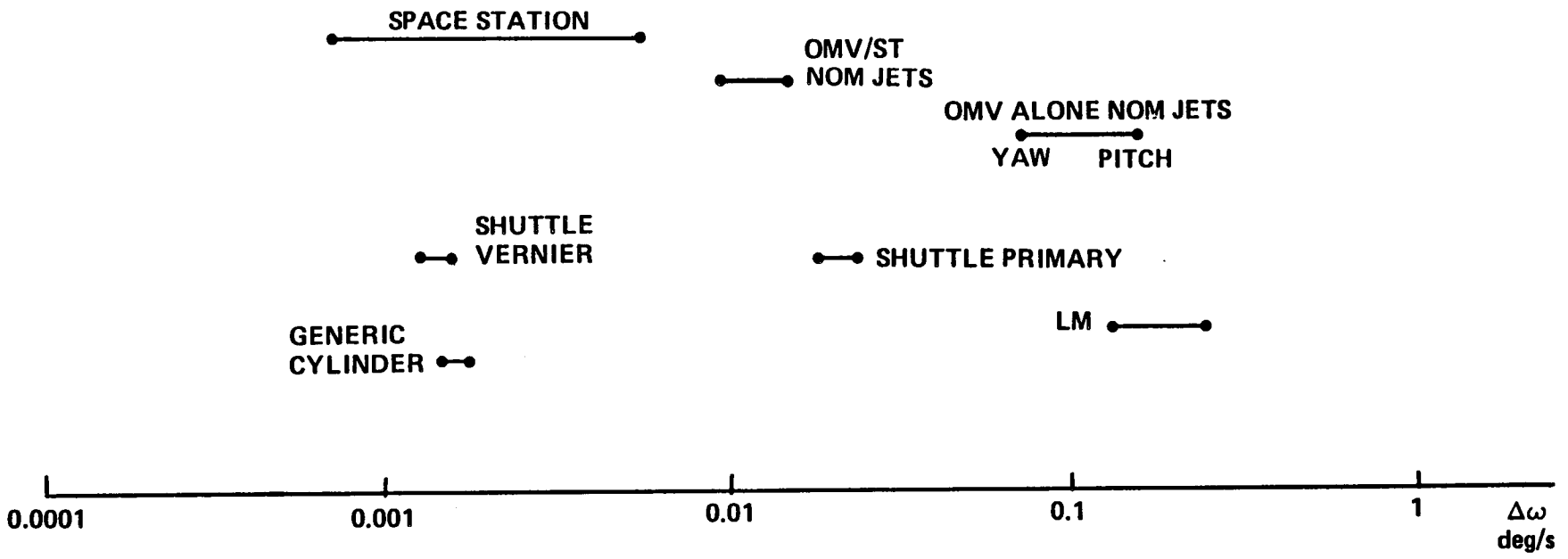
RCS JET CHARACTERISTICS

TYPE	ISP(s)	THRUST(N)	EXAMPLES	COMMENTS
Cold gas	< 100	0.1-10	TRW MRE	Simple, minimal contamination
Monopropellant & catalyst	150-280	0.45-556	TRW, KIDDE	Simple, propellant often corrosive
Hypergolic bipropellant	190-300	102-3870	Marquadt, Rocketdyne, Thiokol	Room temperature propellant, high thrust for given mass
Electric	~1000	10^{-6} lb	Lincoln (Teflon)	High I_{sp}, low thrust
Variable thrust	406	0.66	Resistojet RJ Page	Variable thrust currently unproven, requires electric power

8501M304-2

COMPARISON OF MINIMUM IMPULSE FOR SPACECRAFT ROTATION (80 ms ON TIME)



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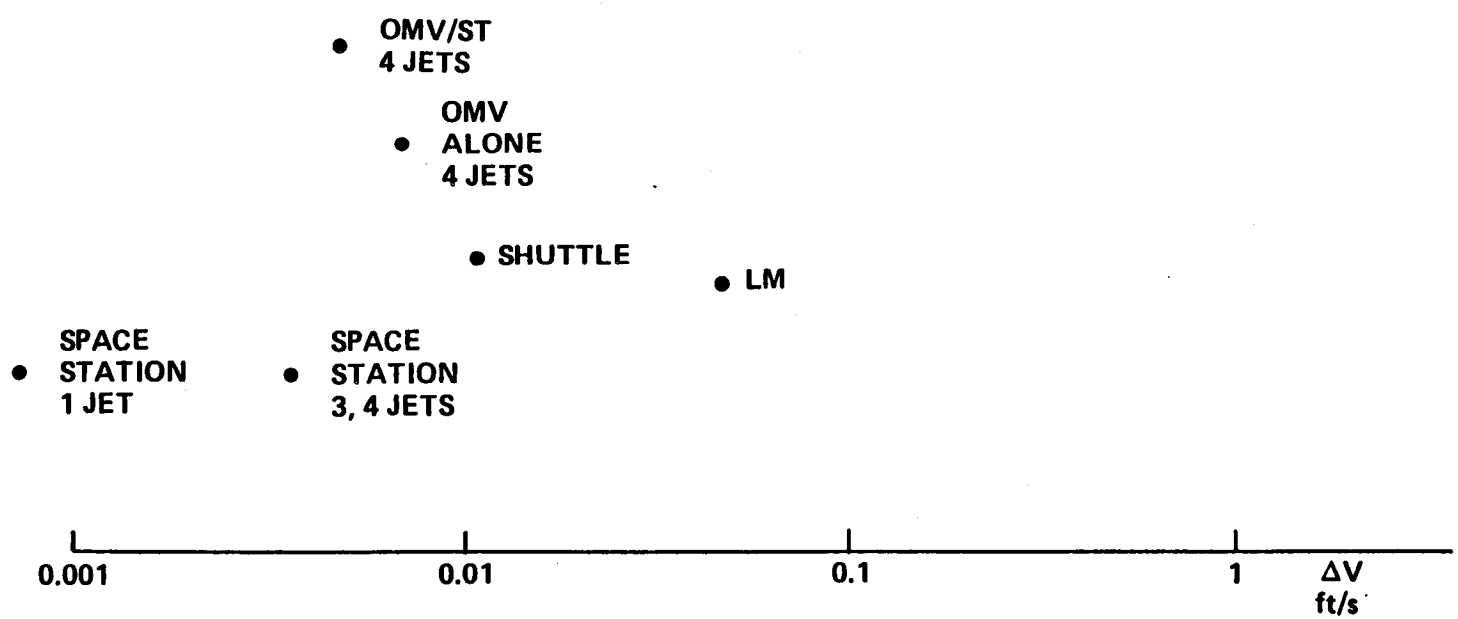
COMPARISON OF MINIMUM IMPULSE FOR TRANSLATION (80 ms ON TIME)



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MOMENTUM EXHANGE DEVICE CHARACTERISTICS

TYPE	RPM	ANG. MOMENTUM CAPACITY N-m-s	MAX TORQUE N-m	EXAMPLES	COMMENTS
Reaction wheels	700-12000	0.7-200	0.03-7	TRW, Bendix, CSDL, Sperry	Reliable, simple control laws
Single gimbal CMGs	3000-9000	150-2500	500-2500	Bendix, Sperry	Highest torque, complicated singularities
Dual gimbal CMGs	4000-8000	10-4000	10-300	Bendix, Sperry	Trades reduced torque for simple singularities

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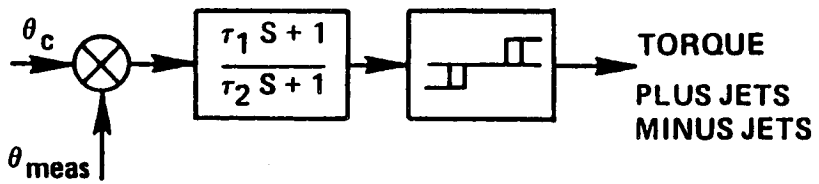
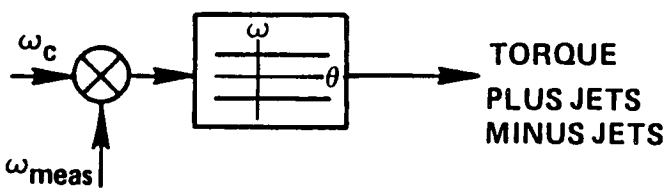
RCS CONTROL LAWS EARLIEST → MERCURY





- Static configuration
- Axes assumed decoupled
  - Diagonal inertia
  - Orthogonal jets
  - Geometric redundancy underutilized
- Poor fuel efficiency
- Analog implementation
- No translation

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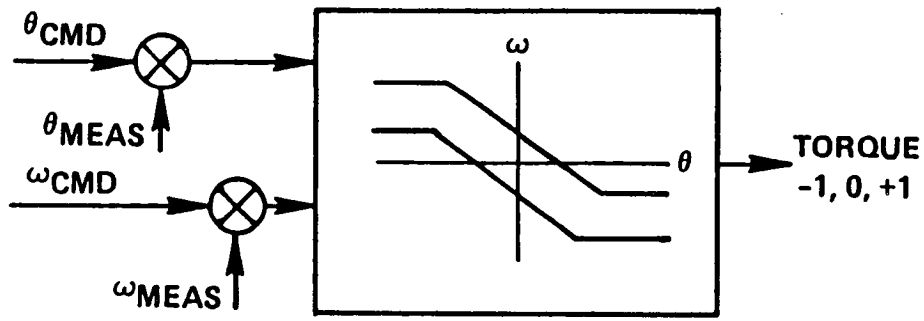
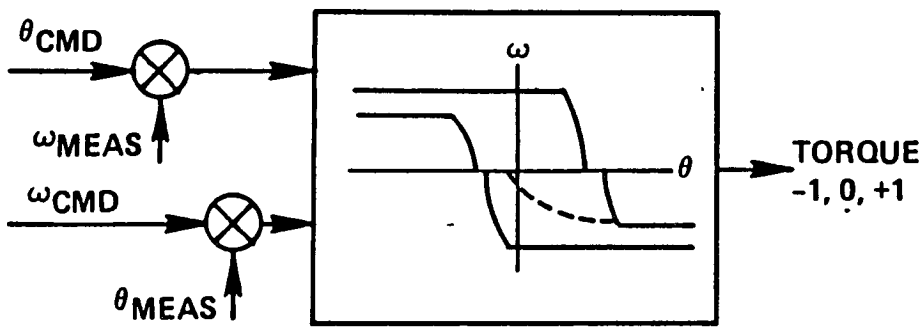
RCS CONTROL LAWS APOLLO SHUTTLE





- Enhanced hysteresis
- Can accommodate limited changes in configuration
- Assumes axes decoupled
- Enhanced fuel efficiency
- Digital implementation
- Translation open loop

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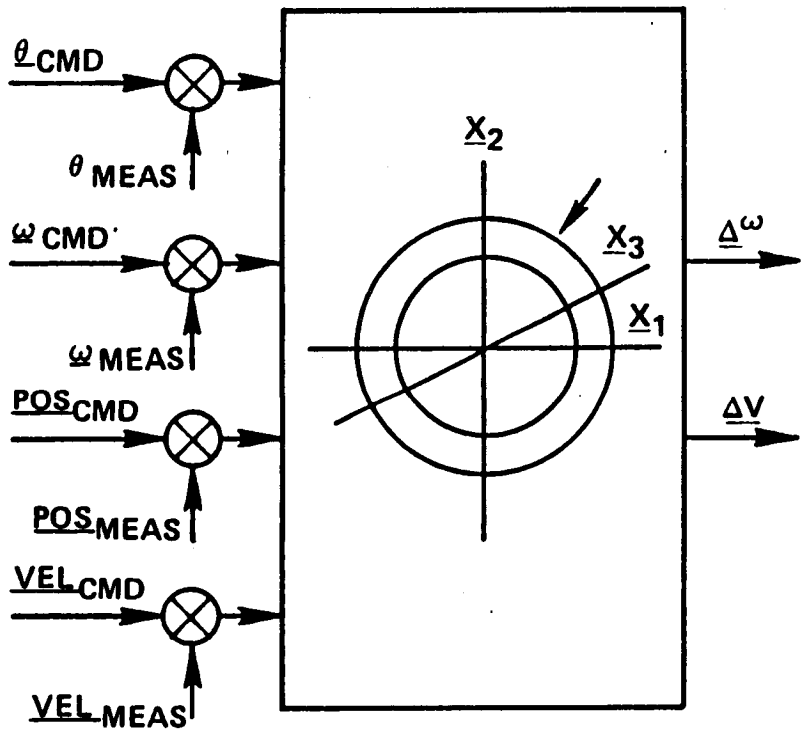
ADVANCED CONTROL LAW PHASE SPACE



- Independent of configuration
- Can accommodate coupled axes
- Highest fuel efficiency
- Digital implementation
- Closed loop position control

8501M304-10

CONTROLLABILITY

- Minimum number of jets given by

$$J \geqslant D + 1 + 2R$$

J = number of jets

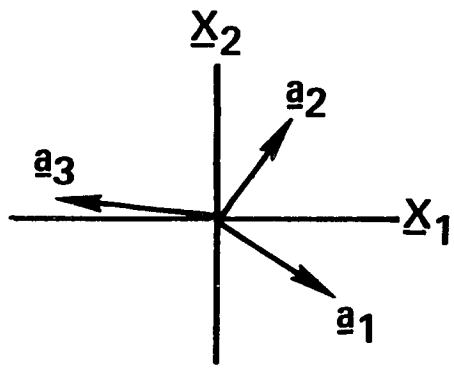
D = degrees of freedom to be controlled

R = number of failures to be tolerated

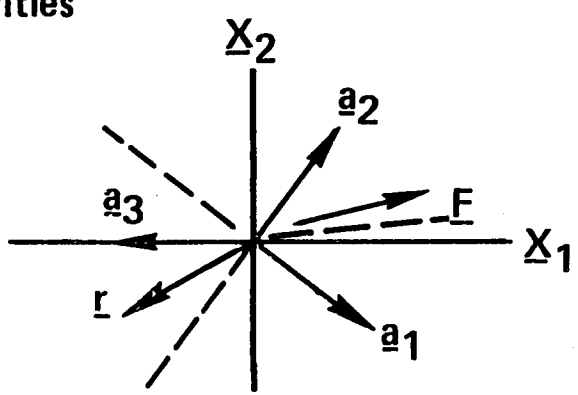
CONTROLLABILITY

- Controllability implies spanning velocity space

Ex: 2 degree of freedom requires at least 3 jets (positive on-time)



Redundancy obtained by counting number of jets each side of plane defined by D-1 activities



8501M304-8

TWO CLASSES OF JET SELECT

- Acceleration oriented
  - Seeks to produce instantaneous acceleration aligned with request
  - Iterated at high rate
- Rate oriented
  - Seeks to find ontimes for jets to produce a desired rate change
  - May run at low rate or on demand

8501M304-7

JET SELECTION CANDIDATES

- Table look-up (fixed)
- Dot product (acceleration)
- Dot product (rate)
- Control axes
- Pseudo inverse
- Optimal linear

8501M304-17

DOT PRODUCT (ACCELERATION)

- Description
  - Calculate $D_i = \underline{\omega} \cdot \underline{a}_i$ each jet
  - Fire the jet with maximum D_i
  - Performance may be enhanced by firing jet with next largest D_i if it exceeds 90% of max D_i
- Attributes
  - Structure independent of number, placement of jets
  - Can accommodate arbitrary number of degrees of freedom
  - Can adjust to changes in mass properties
  - Some fault tolerance
  - Simple

8501M304-4

DOT PRODUCT (RATE)

- Description
  - Set all times = 0
  - Compute $D_i = \underline{a}_i \bullet \underline{\omega}$
  - For max D_i, update ontime $t = t + \frac{D_i}{|a_i|^2}$
  - Decrement $\underline{\omega}$ by $\underline{\omega} = \underline{\omega} - \underline{a}_i \frac{D_i}{|a_i|^2}$
  - Iterate until remaining $\underline{\omega}$ sufficiently small
- Attributes
  - Structure independent of number, placement of jets
  - Can accommodate arbitrary number of degrees of freedom
  - Can adjust to changes in mass properties
  - Some fault tolerance
  - Stopping condition must be carefully chosen
  - Will approximate when no exact solution exists

CONTROL AXES JET SELECTION

- Description
  - Determine a set of D axes spanning velocity space which are exact linear combinations of jet activities e.g.,

$$\underline{b}_i = \sum_j c_{i,j}\, \underline{a}_j$$

  - Map request into this space

$$\underline{\omega}^b = C^b_\omega\, \underline{\omega}$$

  - Scale each component by magnitude of b_i

$$\tau_i = \frac{\omega_i}{|b_i|}$$

  - $t_j = \sum_i \tau_i \dfrac{b_i}{c_{i,j}}$

- Attributes
  - Map of D axes usually changes with jet failures, changes in mass properties
  - Reconfiguration may be impractical inflight
  - Computation generally simple

8501M304-15

PSEUDO INVERSE

- Two sided jets
  - $\underline{t} = A^T (AA^T)^{-1} \underline{\omega}$
- One sided jets
  - Initial solution
    - $\underline{t} = A^T (AA^T)^{-1} \underline{\omega}$
  - Eliminate components with negative ontimes, one at a time
    - Recompute $\underline{t} = A^T (AA^T)^{-1} \underline{\omega}$
    - Repeat until all ontimes positive
- Attributes
  - Can accommodate changes in mass properties
  - One sided convergence not guaranteed

8501M304-5

OPTIMAL LINEAR JET SELECTION

- Description
  - Provide rate change $\left(\frac{\Delta\omega}{\Delta \underline{V}}\right) = \sum_{\text{jets}} \underline{a}_i \, t_i$
  - Minimize f(t), e.g., min fuel
  - Subject to linear constraints

    e.g., $t_i \geqslant 0$

    $t_i \leqslant T$
  - Solve via simplex
- Attributes
  - Fuel optimal
  - Adaptable to changing mass properties
  - Maximum possible fault tolerance
  - Can mix dissimilar jets (primaries, verniers)

8501M304-16

DESIREABLE CAPABILITIES OF ADVANCED SPACECRAFT RCS CONTROLLERS

- Design portable to any spacecraft by parameter changes
- Fuel optimal
- Moderate processing requirements
- High accuracy
- Reasonableness tests
  - Efficiency
  - Controllability
- Can combine different size and type jets
- Capable of adapting to mass property/configuration changes
- Capable of accommodating flexible spacecraft
- Capable of multiple-type actuator operation
- Decoupled 6 DOF
  - Rotation, translation
- On line fault tolerance
- Automatic docking/berthing
- Autonomous operation

8501M304-14

THRUSTER-ASSISTED TETHERS FOR RENDEZVOUS AND PROXIMITY OPERATIONS

JPL

R.A. Laskin

21 February 1985

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

9-92

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AGENDA

TETHER OVERVIEW

TETHER DYNAMICS AND CONTROL FUNDAMENTALS

THRUSTER-ASSISTED TETHERS FOR SATELLITE RETRIEVAL

TETHERS FOR PROXIMITY OPERATIONS

- THRUSTER-ASSISTED TETHERS
- INFLATABLE TETHERS

SUMMARY/CONCLUSIONS

GOAL - DEFINE THE POTENTIAL USE OF TETHERS IN RENDEZVOUS AND PROXIMITY OPERATIONS AND IDENTIFY TETHER UNIQUE CAPABILITIES

TETHER OVERVIEW

Speculations about long connecting strands in space appeared in science fiction as long ago as 1895 in the work of the Russian, Tsiolkovsky. More recently, Gemini 6 and 7 conducted the first spaceborne tether experiment, demonstrating the propensity for two tethered objects to align themselves with the local vertical in a gravity gradient stable configuration. Tethers came under serious consideration for space applications around 1974 at the Smithsonian Astrophysical Observatory (SAO) with the work of the late Giuseppe Colombo. His efforts, and those of many others, will bear fruit with the upcoming flights of the Space Shuttle based Tethered Subsatellite System.

Several applications for spaceborne tethers are listed on the facing page. Rendezvous and Proximity Operations fall roughly under the areas of transportation and remote operations.

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TETHER OVERVIEW

HISTORY

- SCIENCE FICTION - TSIOLKOVSKY (1895)
- EARLY FLIGHTS - GEMINI 6 AND 7 (100 METERS)
- SERIOUS CONSIDERATION - G. COLOMBO (SAO, 1974)
- FUTURE FLIGHT - ITALY/MMC (1987)

POTENTIAL APPLICATIONS

- ATMOSPHERIC SCIENCE
- TRANSPORTATION
- REMOTE OPERATIONS
- ENERGY TRANSFER
- ARTIFICIAL GRAVITY
- CONSTELLATIONS

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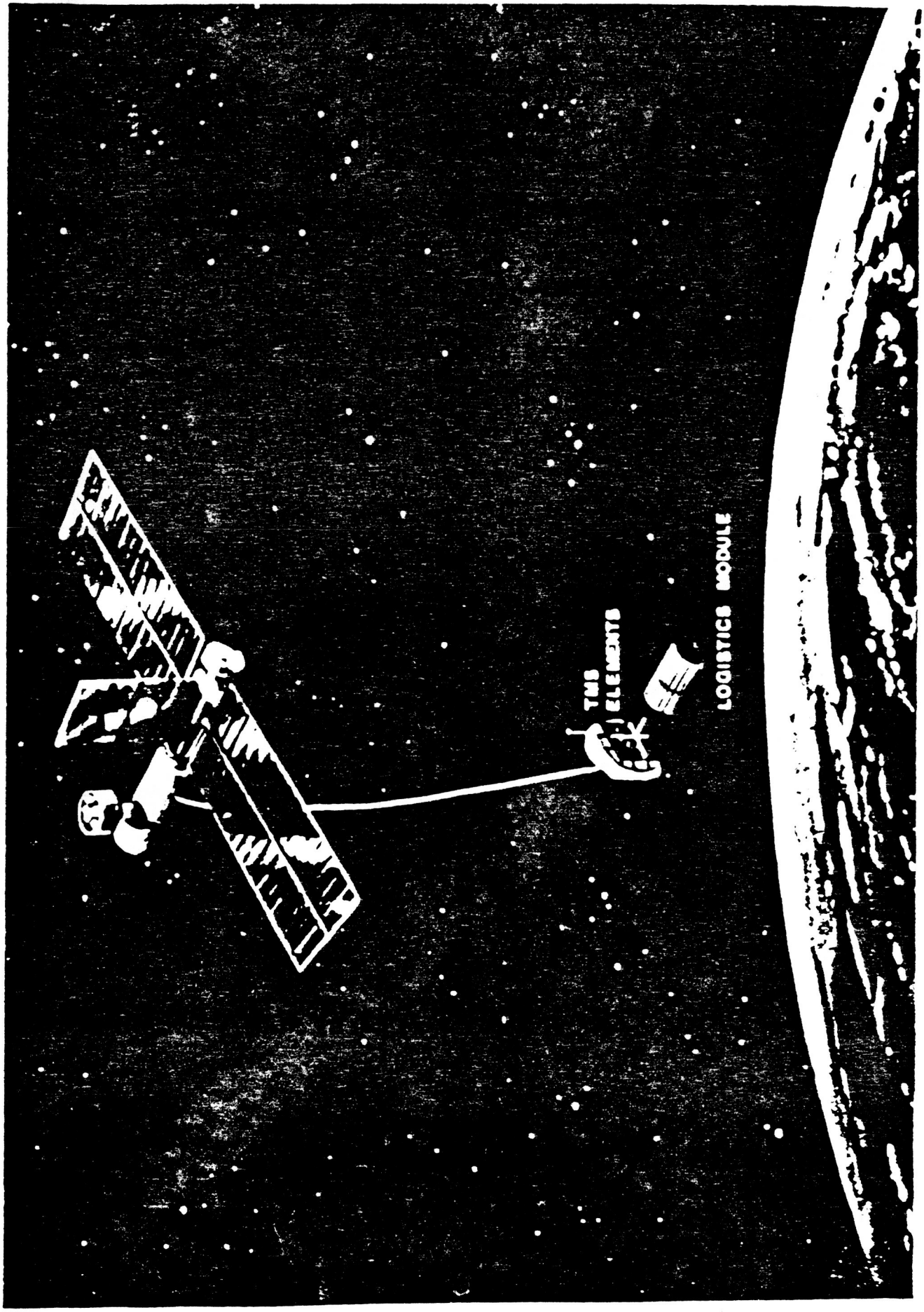
ENVISIONED TETHER APPLICATION

The facing page pictures a space station using a tether to aid in rendezvous and retrieval of a resupply module. In such an application the tether will be deployed over a great distance (perhaps 100 km). The primary benefit lies in the saving of propellant that would otherwise need to be expended for orbit adjust.

Another interpretation is that the figure represents a short tether (~100 m) being used to support remote docking operations.



ORIGINAL PAGE IS
OF POOR QUALITY

TETHER FUNDAMENTALS

When two masses in circular orbit are connected by a tether, the mass-thether-mass system will tend to align itself along the local vertical in a gravity gradient stable equilibrium configuration. Tension is induced in the tether in such a configuration due to the fact that the upper mass is travelling faster and the lower mass slower than they normally would if they were in Keplerian orbits at their respective altitudes. The tension increases with increasing tether length and formally vanishes only when tether length goes to zero. However, in practice, longitudinal vibrations in the tether will cause tension variation which can cause slackness in short tethers (i. e. those less than about one kilometer in length).

Since there is little natural damping in the space environment, the tether system can be expected to oscilate about its equilibrium position. In order of importance these oscillations will include: in-plane librations (librations are rigid body pendulous oscillations of the system), out-of-plane librations, longitudinal vibrations, transverse vibrations, and wave propagation perturbations. The nominal length of the tether is controllable via a reel system. Besides deployment and retrieval the reel system can be used to influence tether oscilations. Aerodynamic drag is the primary environmental effect for tether dynamic analysis.

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TETHER FUNDAMENTALS

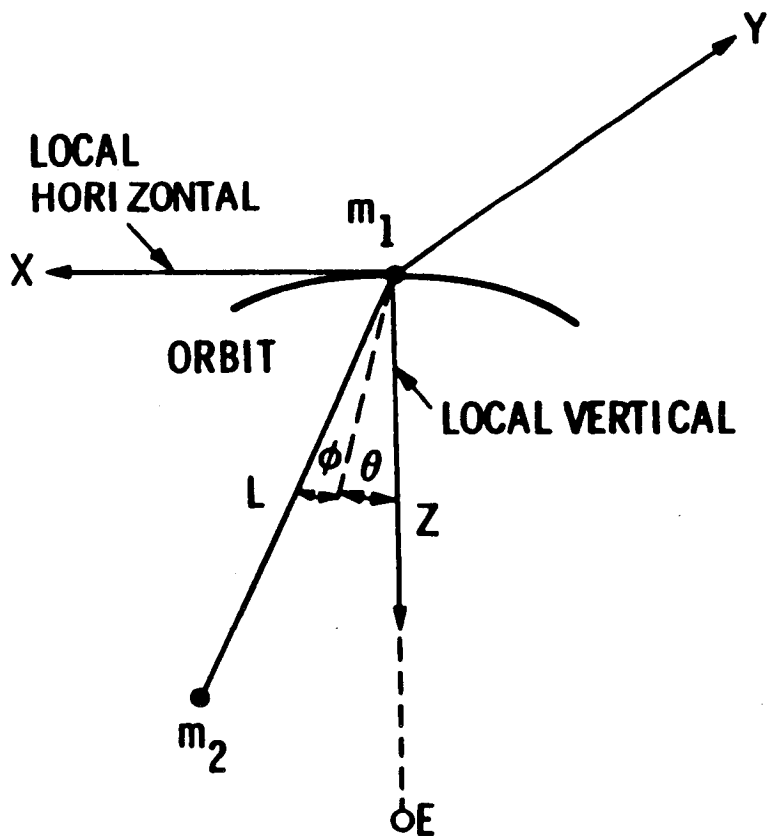
GRAVITY GRADIENT EQUILIBRIUM POSITION - TETHER ALIGNED WITH LOCAL VERTICAL

TETHER TENSION

- INDUCED BY ORBITAL CONSIDERATIONS
  - SYSTEM C.M. IN KEPLERIAN ORBIT
  - END MASSES IN NON-KEPLERIAN ORBITS
- SCALES WITH TETHER LENGTH
  - FORMALLY VANISHES AT L = 0
  - PRACTICALLY CAN VANISH FOR L < 1 km

DYNAMICAL QUANTITIES

- IN-PLANE LIBRATIONS (θ)
- OUT-OF-PLANE LIBRATIONS (ϕ)
- LENGTH VARIATION (INEXTENSIBLE)
- LONGITUDINAL VIBRATIONS
- TRANSVERSE VIBRATIONS
- WAVE PROPAGATION
- AERODYNAMIC DRAG



BASIC TETHER DYNAMICS (NON-VANISHING TENSION)

Tether librational dynamics, for small in and out-of-plane motions, are described by the normalized differential equations on the facing page. Notice that the librational frequencies depend only on the orbital rate and are independent of tether length and the mass of the suspended bodies. Tether length changes via the reel system enter the equations as damping terms. Increasing length (as for deployment) is stabilizing while decreasing length (retrieval) adds negative damping to the system and hence is destabilizing.

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BASIC TETHER DYNAMICS (NON-VANISHING TENSION)

FIXED LENGTH TETHER (LINEARIZED EQUATIONS)

$$\theta'' + 3\theta = Q_\theta$$
$$\phi'' + 4\phi = Q_\phi$$

(PRIME DENOTES DIFFERENTIATION W. R. T. TRUE ANOMALY)

- IN-PLANE LIBRATION FREQUENCY = $\sqrt{3}$ TIMES ORBITAL RATE

  OUT-OF-PLANE LIBRATION FREQUENCY = 2 TIMES ORBITAL RATE

VARIABLE LENGTH TETHER (LINEARIZED EQUATIONS)

$$\theta'' + 2(L'/L)(\theta' + 1) + 3\theta = Q_\theta$$
$$\phi'' + 2(L'/L)\phi' + 4\phi = Q_\phi$$

IMPLICATION: DEPLOYMENT INHERENTLY STABLE

RETRIEVAL INHERENTLY UNSTABLE

TETHER CONTROL WITHOUT THRUSTERS

Tether control problems fall neatly into the categories of deployment, stationkeeping at constant length, and retrieval. Since retrieval is inherently unstable it will recieve the brunt of our attention.

Regardless of the control mode there are to two basic approaches to libration control: tether tension modulation and tether length rate modulation. Both are actuated by the reel system, one using a tensiometer, the other with the help of a tachometer. The two control laws written down are each representative of larger sets that exhibit variations on the basic themes. Note that tension control enjoys an advantage in that it need not employ the libration angles (which may be difficult to sense) in the feedback. This is not a fatal flaw for the length rate approach since these quantities can be estimated from other, more readily available, variables such as tether length and length rate.

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TETHER CONTROL WITHOUT THRUSTERS

CONTROL MODES

- DEPLOYMENT
- STATIONKEEPING
- RETRIEVAL

CONTROL APPROACHES

- TENSION CONTROL [RUPP (1975), KISSEL (1976)]

  $T = K_1 L + K_2 \dot{L} + K_3 L_C$ ($L_C \triangleq$ COMMANDED LENGTH)

  CAN INCLUDE LIBRATION FEEDBACK [BAINUM (1980), MODI (1981)]

- LENGTH RATE CONTROL [MISRA (1980), Xu (1981)]

  $L'/L = K [1 + K_1 \theta' + K_2 \phi'^2]$

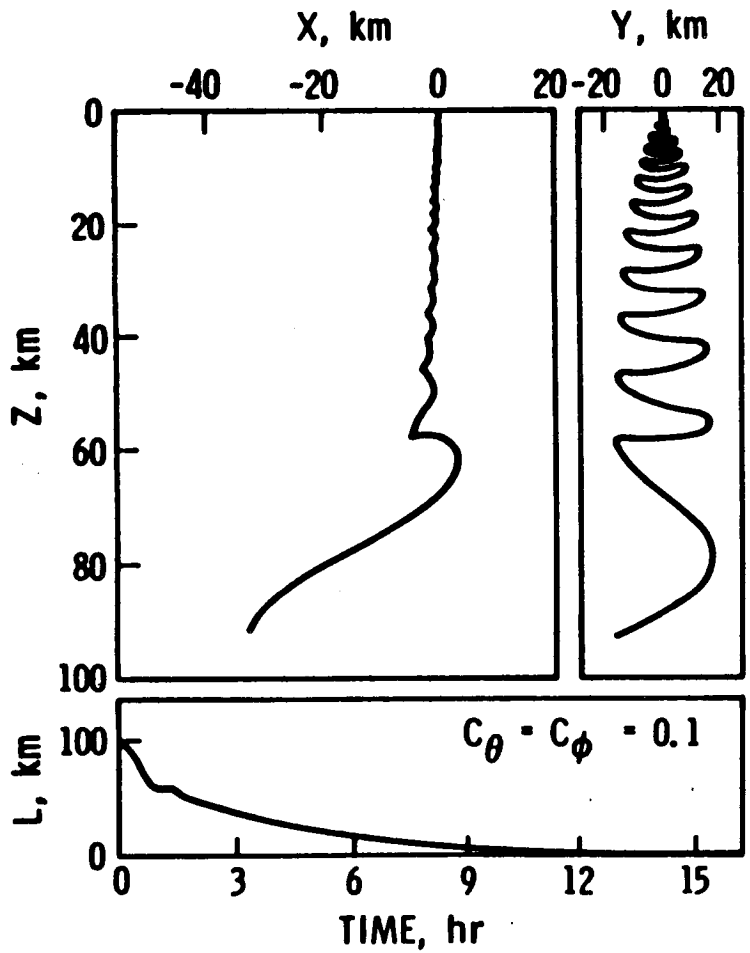
  OTHER FORMS HAVE BEEN PROPOSED
  MAY REQUIRE ESTIMATION OF θ AND ϕ

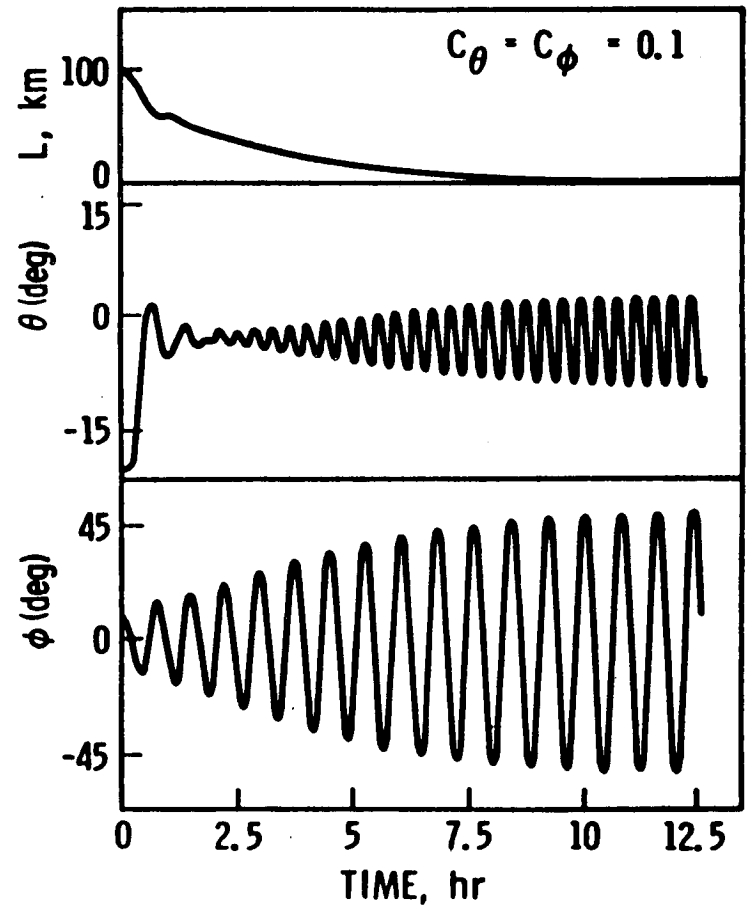
- BOTH APPROACHES PRESUME POSITIVE TETHER TENSION

RETRIEVAL WITHOUT THRUSTER AUGMENTATION - LINEAR TENSION CONTROL

If the linear tension control law of the preceeding slide is used to orchestrate an exponential retrieval of a subsatellite tethered to the Shuttle, the librational behavior is as pictured on the facing page (the plots follow Modi et al, 1982). Although the translational motions of the subsatellite are seen to diminish with time (left hand plot), the libration angles grow until they reach steady limit cycles of substantial amplitudes. More sophisticated control laws, following either the tension or length rate approaches, can decrease the amplitudes of these limit cycles somewhat. However, to date, no control law that relies solely on tether reel control can cause the librations that accompany retrieval to damp completely.

RETRIEVAL WITHOUT THRUSTER AUGMENTATION LINEAR TENSION CONTROL LAW





$i = 90^0$ $L_0 = 100$ km $\phi_0 = 10^0$

$e = 0.00076$ $\theta_0 = -20^0$ $\theta'_0 = \phi'_0 = 0$

9-105

THRUSTER-ASSISTED TETHERS FOR SATELLITE RETRIEVAL

Due to the apparently intractable stability problems associated with tether retrieval, Banerjee and Kane (1982) suggested augmenting the tether reel control with the use of thrusters on the subsatellite. The expectation was that with the addition of state feedback thruster control the retrieval process could be adequately stabilized while propellant savings associated with the use of a tether could be largely preserved. In addition the incorporation of thrusters would guarantee that positive tether tension could be maintained, even at short separation distances. This overcomes a major obstacle to the application of tethers in proximity operations.

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THRUSTER-ASSISTED TETHERS FOR SATELLITE RETRIEVAL

ADVANTAGES

- WELL BEHAVED RETRIEVAL
- TETHER TENSION AT SHORT SEPARATION DISTANCES (<1 km)
- PROPELLANT USAGE SMALL COMPARED TO ALL-PROPULSIVE ORBIT TRANSFER

PROPONENTS

- BANERJEE AND KANE (1982)
- XU, MISRA, AND MODI (1984)

IMPLEMENTATION - STATE FEEDBACK THRUSTER CONTROL LAW
<u>PLUS</u> EITHER TENSION OR LENGTH RATE
TETHER CONTROL

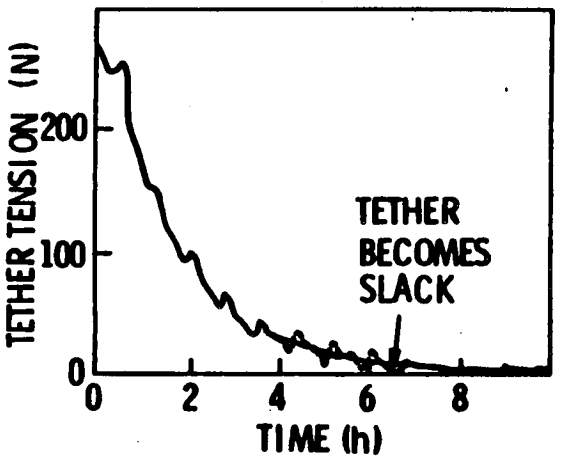
RETRIEVAL WITH THRUSTER AUGMENTATION

The plots on the facing page (due to Banerjee and Kane) illustrate the advantages of using thruster assist in the retrieval process. Four slices of a typical retrieval are presented with the dotted lines representing non-thruster assist and the solid lines representing thruster augmentation in each plot. The out-of-plane thrusters are activated after the librations reach a preset magnitude (~20°) and are seen to quickly stabilize both in and out-of-plane librations. In-plane thrusting is necessary only toward the end of the retrieval to promote a rapid terminal approach. During this phase of the retrieval a thruster aligned with the tether axis is also used to guarantee the maintenance of tether tension. Without this the tether would become slack at a distance of 5.2 km as indicated in the figure.

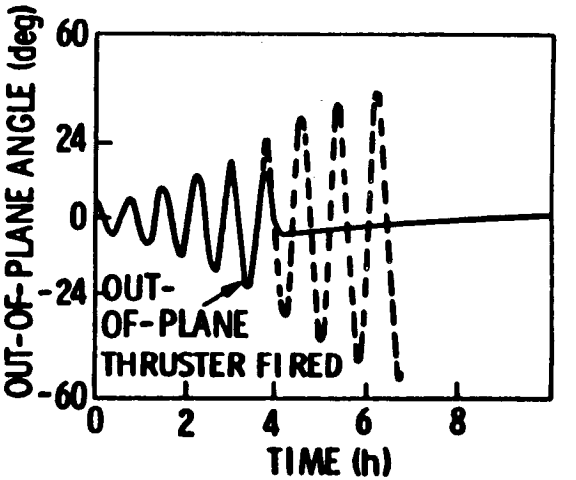
Xu et al have shown, using a somewhat different thruster augmentation law, that ~80% of tether derived fuel savings are preserved when thrusters are incorporated in the retrieval process.

RETRIEVAL WITH THRUSTER AUGMENTATION

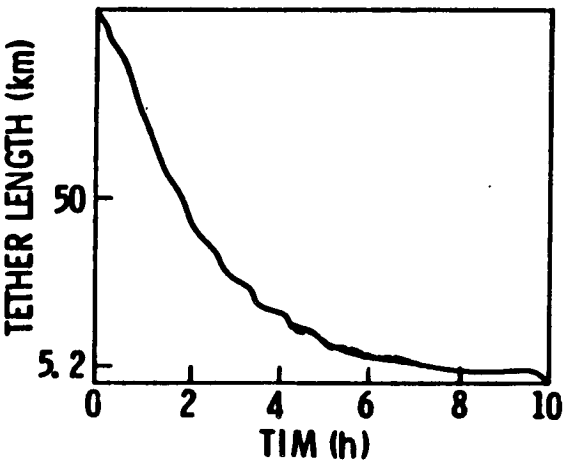
(Banerjee and Kane, 1982)



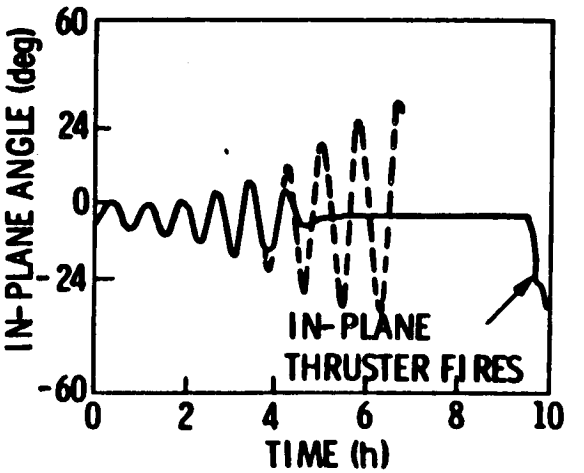
TETHER TENSION WITH AND WITHOUT THRUST AUGMENTATION



OUT-OF-PLANE BEHAVIOR WITH AND WITHOUT THRUSTER AUGMENTATION



COMPARISON OF LENGTH TIME-HISTORIES



IN-PLANE BEHAVIOR WITH AND WITHOUT TRHUSTER AUGMENTATION

TETHERS FOR PROXIMITY OPERATIONS

The proximity operation that we focus on here is the docking of the Space Shuttle and various free flying spacecraft with NASA's envisioned Space Station. Several currently unresolved issues are associated with envisioned Space Station docking operations: provisions for safety of the crew(s) and equipment are foremost; the contamination of the Station by back-firing thrusters must be addressed; a docking sensor system will probably have to be developed; cost is always a consideration. An issue that will strongly impact all the others involves the choice of the active vehicle in the docking process. The conventional wisdom suggests that the Shuttle or free flyer will be the active participant, flying under thruster control into the vicinity of the Station and then navigating in to mate with a Station-attached docking mechanism using an on-board docking sensor. In the sequel we will examine some ways in which the Station (with the help of tethers) might act as the active vehicle for docking.

JPL TETHERS FOR PROXIMITY OPERATIONS

FOCUS

DOCKING OF THE SHUTTLE AND VARIOUS FREE FLYING SPACECRAFT WITH SPACE STATION

ISSUES

- SAFETY
- CONTAMINATION
- SENSING
- ACTIVE VEHICLE
  - SPACECRAFT/SHUTTLE
  - STATION
- COST

GENERIC DOCKING OPTIONS

For present purposes we consider three generic docking options: spacecraft (or Shuttle) active docking; Space Station active docking; a hybrid approach where both the spacecraft and Station are active at some point in the process. Various hard and soft docking scenarios are under consideration for spacecraft active docking. Although this approach has the advantage of requiring minimal Space Station capability, there is the balancing disadvantage that each spacecraft must possess maximal capability to carry on docking sensing, processing, and actuation. The distribution of this sophisticated capability among numerous spacecraft does not seem to be a cost effective approach. Further disadvantages of the spacecraft active option involve the issue of safety. There are clearly risks involved in allowing a rather massive vehicle to fly up to and "collide" with the Space Station under autonomous control. Even in the case of the Shuttle, which will be under manual control, Wang et al (1984) have shown that, due to the resolution of the Shuttle RCS/VRCS which results in excessive residual rates, buckling of Station's solar panels might result from Shuttle "soft" docking. Contamination from (typically hydrazine) thrusters is also a disadvantage of the spacecraft active approach.

Space Station active docking might involve the use of the Teleoperated Maneuvering System (TMS) to act as a tugboat that proceeds from the Station, remotely docks with the incoming spacecraft, and ferries the craft to the close proximity of the Station (~10 m) under cold gas thruster control. At this point, in order to avoid the "collision" associated with hard/soft docking, the Station Remote Manipulator System (RMS) could be used to "catch" the docking vehicle. An alternative to this scenario envisions tethering the TMS to the Station which allows a vernier final approach where the tether pulls while the TMS supplies a nearly counterbalancing push. This would eliminate the need for RMS mediation while supporting a process that is always under positive, active, manual control. The incorporation of inflatable tethers (to be described shortly) could provide a fail-safe, variable stiffness, mechanical connection during the critical terminal approach phase of the docking process.

Various hybrid approaches to the problem can be envisioned. They will all share, to greater or lesser degree, the disadvantages of the spacecraft active option.

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GENERIC DOCKING OPTIONS

SPACECRAFT ACTIVE DOCKING

- HARD/SOFT
- ADVANTAGE - MINIMAL STATION CAPABILITY
- DISADVANTAGES
  - MAXIMAL SPACECRAFT CAPABILITY (FOR MANY S/C)
  - RISKY
    - AUTONOMOUS FREE FLYER DOCKING RAISES SAFETY ISSUES
    - SHUTTLE RESIDUAL RATES MAY BE EXCESSIVE (WANG, 1984)
  - CONTAMINATION

STATION ACTIVE DOCKING

- TMS AS "TUGBOAT" WITH STATION RMS MEDIATION
- TMS ON TETHER (I.E., THRUSTER-ASSISTED TETHER)
  - ALLOWS VERNIER TERMINAL APPROACH WITH THRUSTER PUSH, TETHER PULL
  - ELIMINATES NEED FOR RMS
  - SINGLE SYSTEM COULD SUPPORT RETRIEVAL AND DOCKING
  - INCORPORATION OF INFLATABLE TETHERS POSSIBLE

HYBRID APPROACH (E.G., HARD/SOFT DOCKING WITH STATION RMS MEDIATION)

INFLATABLE TETHERS FOR TERMINAL APPROACH WITH ACTIVE STIFFNESS CONTROL

An inflatable tether is essentially a thin walled tube that can be pressurized internally with either a gas or liquid. Its primary benefit for docking application lies in its ability to provide a positive mechanical connection with resistive force between Station and the docking craft. This clearly enhances docking safety. In addition the tether pressure can be modulated to provide variable stiffness which can be used to significantly augment the system's natural damping. This might render thrusters unnecessary or at least curtail their use in the near vicinity of the Station where the contamination issue is most critical. The scenario pictured on the facing page shows the use of three inflatable tether bundles to effect terminal docking (and berthing) of the Space Shuttle. For free flying spacecraft with smaller inertias than the Shuttle, the use of a single tether bundle should be possible.

The facing chart also suggests a form of docking sensing suitable to the inflatable tether approach. If one or more of the tethers are coated with a recently developed piezoelectric polymer film, which produces voltages proportional to tether displacements, vehicle realtive rates and displacements can be accurately sensed.

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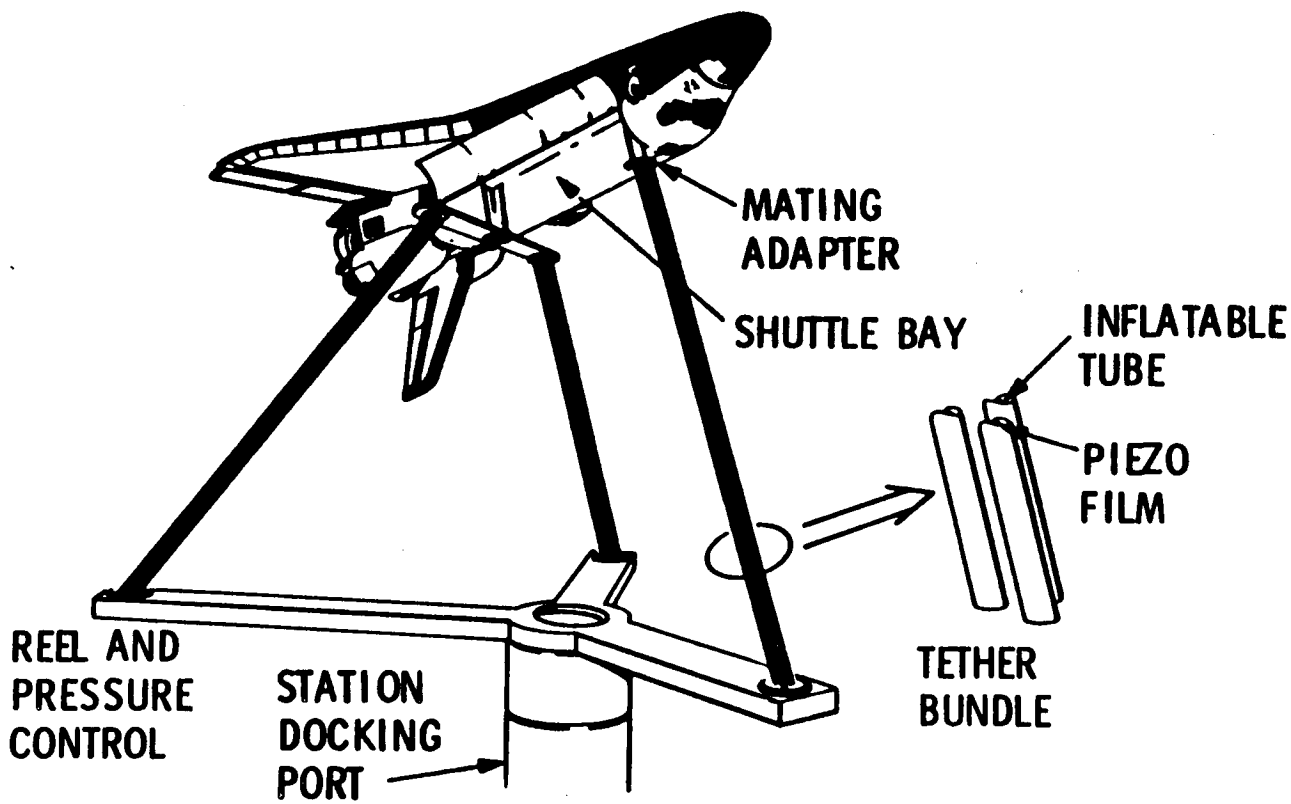
INFLATABLE TETHERS FOR TERMINAL APPROCH WITH ACTIVE STIFFNESS CONTROL

- PROVIDES MECHANICAL CONNECTION WITH RESISTIVE FORCE
- PRESSURE CONTROL TO AID/REPLACE THRUSTERS
- NO NEED FOR RMS
- PROVIDES READY MADE BERTH
- PROVIDES SENSING WITH USE OF PIEZO ELECTRIC POLYMER FILM

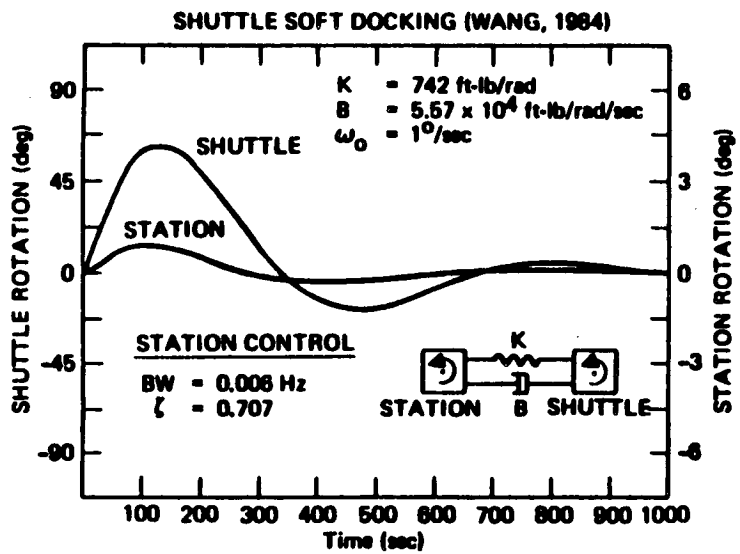


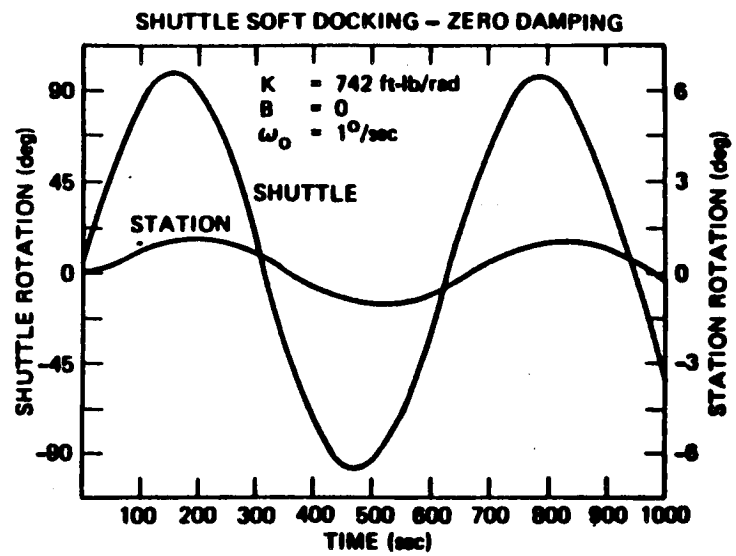
TETHER PRESSURE MODULATION FOR ACTIVE STIFFNESS CONTROL

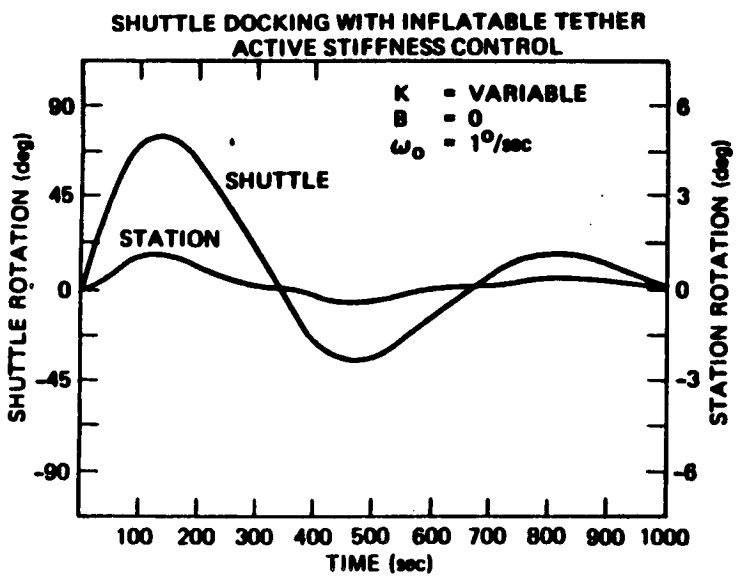
On the facing page the viability of modulating tether stiffness to augment damping behavior is demonstrated via simulation. The model analyzed (due to Wang, 1984) is shown in the upper left hand plot. Wang examined the effect of expected Shuttle residual rates on soft docking as represented by a simple rotational mass-dashpot arrangement. He showed that with a docking mechanism soft enough to prevent buckling of Station's solar panels, unacceptalbly high Shuttle angular excursions (~60°) result. These excursions are unacceptable because the docking mechanism he envisioned would have dimensions on the order of meters. An inflatable tether system, on the other hand, could easily be tens (perhaps hundreds) of meters in extent. Large relative angular excursions would then be possible. The problem is in providing adequate damping over such large distances. Without damping the response is as pictured in the upper right hand plot. Peak excursions have increased and convergent behavior is nowhere in evidence after 15 minutes (the system should be slightly damped due to the prescence of the Station control system). Dramatic improvements are possible with the incorporation of active stiffness control as pictured at lower left. Through the use of stiffness levels comparable to those used by Wang (lower right plot) a damping ratio of close to 0.707 can be achieved.

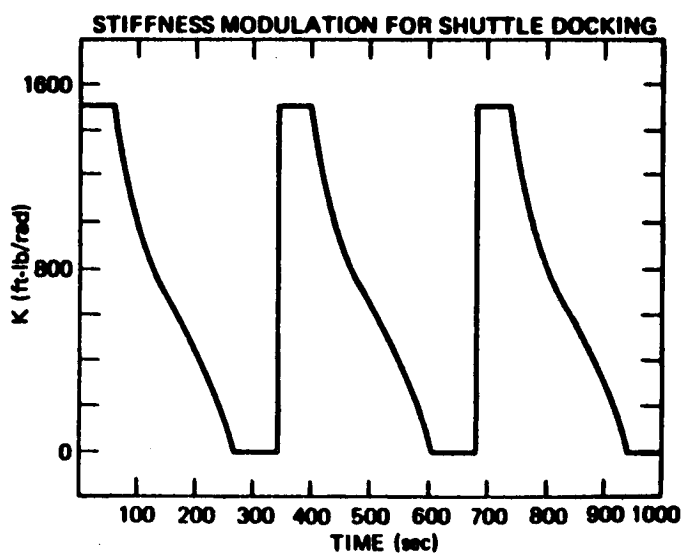
Work on active stiffness control via inflatable tether pressurization, including the effects of higher modes, is on-going at JPL.

TETHER PRESSURE MODULATION FOR ACTIVE STIFFNESS CONTROL









SUMMARY/CONCLUSIONS

Tethers have potential uses in the realm of rendezvous operations for the retrieval of satellites from different orbital altitudes with significant fuel savings. However, some form of thruster augmentation to established tether reel control laws will be necessary to provide stabilization and maintain tether tension. While a start has been made in this direction considerable further work is indicated to minimize the use of time and fuel in the retrieval process.

Thruster-assisted and inflatable tethers show promise in the area of proximity operations where they may provide a safe, contamination free, cost effective means of docking a range of space vehicles to the Space Station. The use of inflatable tethers will also provide a ready made berthing port.

Although a significant amount of mathematical modeling of tether systems has already been done, the development of component hardware is at a very early stage of maturity. Considerable further work, especially in the component area, is necessary before tether technology can be considered flight ready.

Acknowledgment

The research described herein was performed at the Jet Propulsion Laboratory, California Institute of Technology, under the sponsorship of the National Aeronautics and Space Administration.

JPL

SUMMARY / CONCLUSIONS

TETHERS FOR SATELLITE RETRIEVAL

- WITHOUT THRUSTER AUGMENTATION RETRIEVAL IS ACCOMPANIED BY LARGE LIMIT CYCLE OSCILLATIONS
- THRUSTER AUGMENTATION SHOULD PROVIDE REQUISITE STABILIZATION WHILE PRESERVING FUEL SAVINGS
- CONTROL LAW OPTIMIZATION REQUIRED

TETHERS FOR PROXIMITY OPERATIONS

- THRUSTER-ASSISTED TETHERS CAN PROVIDE VERNIER FINAL APPROACH
- INFLATABLE TETHERS CAN PROVIDE ENHANCED SAFETY AND CONTROLLABILITY WITH DIMINISHED CONTAMINATION

TECHNOLOGY DEVELOPMENT STATUS

- MUCH ANALYTIC MODELING HAS BEEN DONE
- COMPONENT TECHNOLOGY IN EARLY STAGES OF MATURITY
- CONSIDERABLE FURTHER EFFORT NECESSARY TO ACHIEVE TECHNOLOGY READINESS

ED4590

REMOTELY PILOTED VEHICLES: CONTROLABILITY ISSUES WILL FOCUS ON RENDEZVOUS AND DOCKING OF SPACE VEHICLES

ELEMENTS OF RPV SYSTEM AFFECTING CONTROLABILITY INCLUDE:

- REMOTE SENSING: ACQUIRE INFORMATION WHICH WILL PERMIT PILOT DETERMINATION OF RELATIVE ATTITUDE AND POSITION OF VEHICLES AND THEIR RELATIVE RATES
- COMMUNICATIONS: TRANSMIT SUFFICIENT INFORMATION TO THE PILOT TO PERMIT CONFIDENT DECISION–MAKING; RELIABLY TRANSMIT PILOT'S COMMANDS TO THE RPV
- REMOTELY–PILOTED VEHICLE: PROVIDE CONSISTENT AND PREDICTABLE RESPONSES TO COMMANDS; CONTROL RESPONSIVENESS AND MODES MATCHED TO THE PILOT AND THE MISSION
- CONTROL STATION: PRESENT REMOTE–SENSING INFORMATION CLEARLY AND UNAMBIGUOUSLY; REMOTE CONTROLS SHOULD COMFORTABLY TRANS–LATE HAND MOVEMENTS INTO CORRESPONDING VEHICLE MOVEMENTS
- TARGET VEHICLE: ITS CHARACTERISTICS AND BEHAVIOR MUST BE CONSIDERED IN THE DESIGN OF RPV SYSTEMS

ED4593

TARGET SPACECRAFT DYNAMICS–DOCKING STRATEGIES

- INERTIALLY STABILIZED: FLY STRAIGHT TO TARGET; MATCH ATTITUDE WHILE APPROACHING DOCKING FIXTURE
- SINGLE AXIS ROLL RATE: FLY STRAIGHT TO TARGET MATCH ROLL RATE AND ANGLE, CORRECT PITCH & YAW ANGLES DURING FINAL APPROACH
- SINGLE AXIS PITCH OR YAW RATE:
  - BEST TECHNIQUE–APPROACH TARGET ON A TRAJEDTORY LYING IN THE PLANE OF ROTATION, ATTEMPTING TO INTERCEPT DOCKING FIXTURE AS IT ALIGNS ITSELF WITH THE OMV
  - IF THE DOCKING FIXTURE PASSES BY SOONER THAN EXPECTED BOTH FORWARD AND LATERAL ACCELERATION WILL BE REQUIRED TO CONTINUE CLOSING IN. ATTITUDE RATE HOLD CAN BE USED TO MAINTAIN ANGULAR ALIGNMENT DURING THE FINAL PHASE
- MULTIPLE AXIS ATTITUDE RATES: ABOVE TECHNIQUES CAN BE USED IN COMBINATION AS REQUIRED. PREDICTING TARGET MOTION IS MUCH MORE DIFFICULT; LAST–MINUTE TRANSLATIONAL AND ANGULAR ADJUSTMENT ARE ALMOST ALWAYS NEEDED

CHASE VEHICLE DESIGN – FLIGHT CONTROL SYSTEM

TRANSITIONAL CONTROL

- OPEN–LOOP ON–OFF ACCELERATION MODE
  - PROVIDES GOOD FUEL ECONOMY AND RESPONSIVE HANDLING QUALITY
- PULSE MODE
  - USEFUL FOR FINE ADJUSTMENTS DURING PRECISION DOCKINGS
- CLOSED–LOOP POSITION CONTROL
  - NOT PRACTICAL; REQUIRES ELABORATE POSITION–SENSING APPARATUS

ATTITUDE CONTROL

- OPEN–LOOP ON–OFF ACCELERATION MODE
  - DIFFICULT TO USE DUE TO GRAVITY GRADIENT AND OTHER ATTITUDE DISTURBANCES
- CLOSED–LOOP RATE–COMMAND MODE
  - PERMITS INERTIAL STABILIZED OR LOCAL–VERTICAL ALIGNED FLIGHTS; AUTOMATICALLY COMPENSATES FOR DISTURBANCES
  - REDUCES PILOT WORKLOAD
  - REQUIRES RATE GYROS, PHASE–PLANE AUTOPILOT
- ATTITUDE RATE – HOLD FEATURE
  - ALLOWS OMV TO MATCH ATTITUDE OF TUMBLING SATELLITES; REDUCES PILOT WORKLOAD
  - VERY SIMPLE AND INEXPENSIVE TO INCLUDE

ED4591

CHASE VEHICLE DESIGN – THRUSTER FIRING LOGIC

DESIGN GOALS:

- PROVIDE PREDICTABLE RESPONSE TO COMMAND INPUTS (ROLL, PITCH, YAW, X, Y, AND Z, INCLUDING ALL POSSIBLE COMBINATIONS)
- MINIMIZE FUEL CONSUMPTION (WHEN POSSIBLE)
- ACCOMMODATE ONE OR MORE FAILED THRUSTERS (WITH REDUCED ACCELERATION ABILITY)

METHODS OF IMPLEMENTATION*

- LOGICAL DECISION TREE: SMALL MEMORY, CPU TIME REQUIREMENTS EASILY ACCOMMODATES LARGE NUMBER OF THRUSTERS PRIORITY CONTROL EASILY DETERMINED
- LOOKUP TABLE: VERY SMALL CPU TIME REQUIREMENTS, VERY FLEXIBLE CONTROL PRIORITIES POSSIBLE MEMORY NEEDED PROPORTIONAL TO NUMBER OF THRUSTERS
- GENERALIZED MATRIX INVERSE: EASILY ACCOMMODATES FAILED THRUSTERS LARGE CPU TIME REQUIREMENTS

CONTROL PRIORITIES: X–AXIS TRANSLATION SHOULD RECEIVE TOP PRIORITY; ESSENTIAL DURING FINAL PHASE OF DOCKING.

ED4587

CHASE VEHICLE DESIGN – CHOOSING THRUSTER SIZES

- AFFECTS MINIMUM, MAXIMUM AVAILABLE ACCELERATION
- THRUSTERS SHOULD PRODUCE ANGULAR AND TRANSLATIONAL ACCELERATIONS FALLING WITHIN THE ENVELOPE SHOWN AT RIGHT TO ASSURE OPTIMAL HANDLING QUALITIES. THIS ENVELOPE WAS DERIVED FROM PILOT EVALUATION OF EXISTING SPACE VEHICLES.
- TARGET VEHICLES HAVING HIGH TUMBLING RATES DEMAND LARGER THRUSTERS.
- LARGER THRUSTERS MAKE FINE ALIGNMENT CORRECTIONS MORE DIFFICULT, CAN RESULT IN PILOT OVER–CONTROL.
- SMALL THRUSTERS CAN RESULT IN OVER–CONTROL DUE TO PILOT NOT NOTICING SMALL CHANGES IN VELOCITY. MORE KNOWLEDGE OF TARGET DYNAMICS NEEDED SO THAT MANEUVERS CAN BE PLANNED FURTHER IN ADVANCE.
- LARGER THRUSTERS ARE USEFUL FOR EMERGENCY EVASIVE MANEUVERS.
- LARGER THRUSTERS DO NOT NECESSARILY DECREASE FUEL ECONOMY. WITH TUMBLING TARGETS, THEY CAN RESULT IN IMPROVEMENT.

ED4592

CHASE VEHICLE DESIGN – DOCKING FIXTURE REQUIREMENTS

- FIXTURE – DETERMINED END–CONDITION REQUIREMENTS INCLUDE:

  MAXIMUM RELATIVE ROLL, PITCH, AND YAW ANGLES
  CAPTURE RADIUS (MAXIMUM DISTANCE OFF–CENTER ALLOWED)
  MINIMUM AND MAXIMUM FINAL IMPACT VELOCITY
  (THESE PARAMETERS ARE OFTEN INTER–RELATED)

- DOCKING FIXTURES DEMANDING SMALLER ALIGNMENT ANGLES OR CAPTURE RADIUS WILL RESULT IN MORE FUEL CONSUMPTION, TIME NEEDED.

- PRECISE ALIGNMENT REQUIREMENTS MAY NECESSITATE VARIABLE–THRUST CONTROL SYSTEM DESIGN, INCLUDING AUTOPILOT FEATURES.

- NARROW IMPACT VELOCITY RANGE MAY NECESSITATE RANGE RATE RADAR SYSTEM.

- DOCKING WITH TUMBLING TARGETS HAVING UNUSUALLY TIGHT END–CONDITION CONSTRAINTS MAY PROVE IMPOSSIBLE.

ED4585

CONTROL STATION DESIGN – PILOT CONTROL JOYSTICKS

- 6 DEGREES OF FREEDOM MUST BE CONTROLLED
- RIGHT HAND CONTROLS ROTATION (PRECISION MORE IMPORTANT HERE)
- LEFT HAND CONTROLS TRANSLATION (ON–OFF ACCELERATION)
- PROPORTIONAL CONTROLS: LINEAR VS. NONLINEAR
  - LINEAR CONTROLS PROVIDE MORE PREDICTABLE, UNIFORM RESPONSE
  - NONLINEARITY PERMITS SMALL, PRECISE ADJUSTMENTS AND LARGE, COARSE MOVEMENTS (SQUARE–LAW CHOSEN FOR OMV SIMULATION)
- RESOLUTION OF PROPORTIONAL JOYSTICKS LIMITS DOCKING ACCURACY
- MOTION OF HAND CONTROLLERS RESULTS IN SIMILAR MOVEMENT OF OMV
- NO POSSIBLE MOVEMENT OF EITHER JOYSTICK SHOULD REQUIRE AWKWARD PILOT MOVEMENTS OR POSITIONS
- PILOT SHOULD BE ABLE TO REST ARMS COMFORTABLY WHEN NOT USING JOYSTICKS
- EFFORT NEEDED TO MOVE JOYSTICKS SHOULD BE LARGE ENOUGH TO PREVENT ACCIDENTAL MOVEMENT, BUT NOT ENOUGH TO CAUSE PILOT FATIGUE
- HIGHER SAMPLING RATES IMPROVE RELIABILITY AND ACCURACY

ED4588

CONTROL STATION DESIGN – INFORMATION DISPLAYS

VIDEO MONITOR

- SCREEN SIZE TRADEOFF:
  - LARGE SCREEN PROVIDES MORE DETAIL
  - SMALLER SCREEN REQUIRES LESS EYE MOVEMENT
  - A RELATIVELY SMALL SCREEN WAS CHOSEN FOR THE SIMULATOR (14 INCHES)
- SCREEN SHOULD BE PERPENDICULAR TO THE PILOT'S LINE OF SIGHT TO AVOID PERSPECTIVE DISTORTION
- MONOCHROME VIDEO DISPLAY ADEQUATE FOR ALMOST ALL MISSIONS
- PILOT SHOULD BE ABLE TO ADJUST BRIGHTNESS/CONTRAST FOR MOST COMFORTABLE VIEWING
- RESOLUTION AND FRAME RATE SHOULD BE KEPT AS HIGH AS POSSIBLE
  - RESOLUTION LIMITS FINAL PRECISION OF DOCKING (500 x 500 USED IN SIMULATION)
  - FRAME RATE LIMITS PRECISION AND TOLERABLE TUMBLE RATES (30 FRAMES PER SECOND USED IN SIMULATION)
- CROSSHAIRS OR TEMPLATE SHOULD BE PLACED ON SCREEN TO ASSIST PILOT IN JUDGING DISTANCE AND ALIGNMENT (ESPECIALLY IMPORTANT IF RANGE RADAR NOT USED)

ED4586

RPV – CONTROL STATION COMMUNICATIONS

DATA RATE REQUIREMENTS

- UPLINK PROPORTIONAL TO COMMAND RESOLUTION AND UPDATE RATES
- DOWNLINK PROPORTIONAL TO VIDEO FRAME RATE RESOLUTION, AND RADAR SAMPLING RATE, DATA PRECISION

TIME DELAY CONSIDERATIONS

- SOURCES: EARTH–GEO TRAVEL TIME (1/8 SECOND EACH TRIP)
  GROUND–BASED NETWORK PROPAGATION (REAL–TIME VARIABLE)
- TOTAL DELAY FOR PROPOSED SYSTEM:
  - SATELLITE LINKS = 2 x 2 x 2 x 1/8 = 1 SECOND
  - GROUND DELAYS ESTIMATED 1 – 4 SECONDS
- SMALL TIME DELAYS (LESS THAN 2 SECS) HAVE LITTLE EFFECT ON OVERALL DOCKING ABILITY
- PREDICTIVE DISPLAYS CAN COMPENSATE FOR LARGE CONSTANT DELAYS WHEN TARGET SPACECRAFT DYNAMICS ARE KNOWN
- UNPREDICTABLE VARIABLE DELAYS COULD MAKE RELIABLE DOCKING WITH TUMBLING SATELLITES DIFFICULT OR IMPOSSIBLE

ED4610

AFFECT OF INCREASING TUMBLE RATES

TUMBLE AXIS	ROLL				PITCH				ROLL, PITCH & YAW			
PILOT	A	B	C	D	A	B	C	D	A	B	C	D
FINAL Y–Z RSS DOCKING PROBE POSITION	W	W	U	W	U	U	U	U	W	W	U	W
FINAL PITCH–YAW RSS DOCKING PROBE ATTITUDE	W	W	U	W	U	U	I	U	W	W	U	W
FINAL RELATIVE ROLL ANGLE	U	U	W	W	U	I	U	I	W	W	W	W
FINAL Y–Z RSS DOCKING PROBE VELOCITY	U	U	U	U	U	U	I	W	W	W	W	W
FINAL X–AXIS CLOSING RATE	U	U	U	U	U	U	U	W	U	U	W	W
TOTAL FUEL USED	W	W	W	W	W	W	W	W	W	W	W	W
TIME REQUIRED	U	U	U	U	U	U	U	U	U	I	W	W
TOTAL NUMBER OF THRUSTER FIRINGS	W	W	W	W	WORSE AT MODERATE RATES THAN SMALL OR LARGE				W	W	W	W

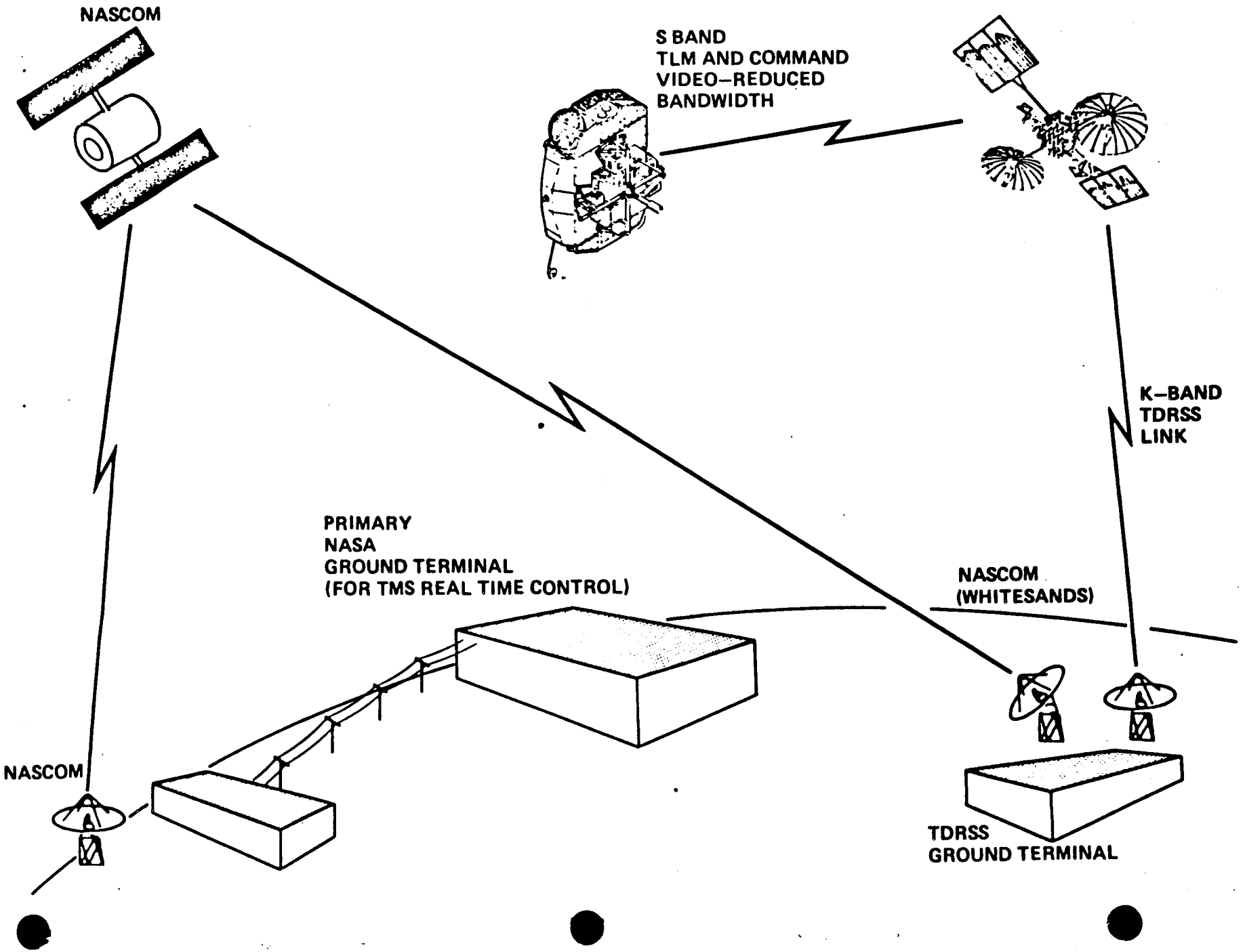
I = IMPROVES WITH RATE W = WORSENS WITH RATE U = UNAFFECTED

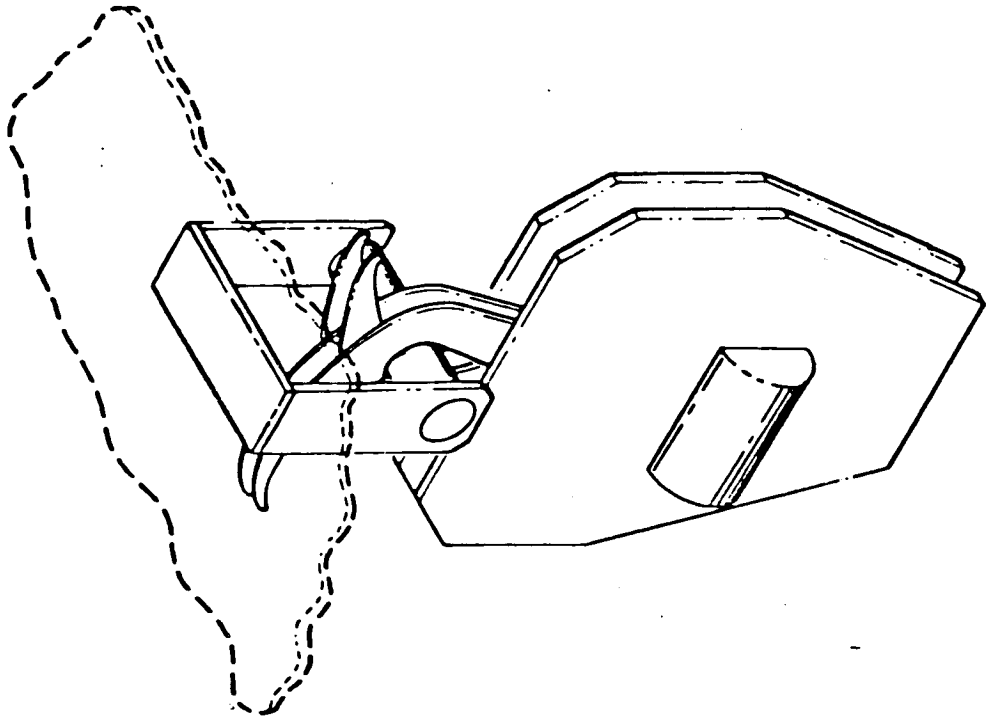
RATES INVESTIGATED: 0–2 DPS ROLL; 0–2 DPS PITCH; 0–1 DPS ROLL, PITCH & YAW

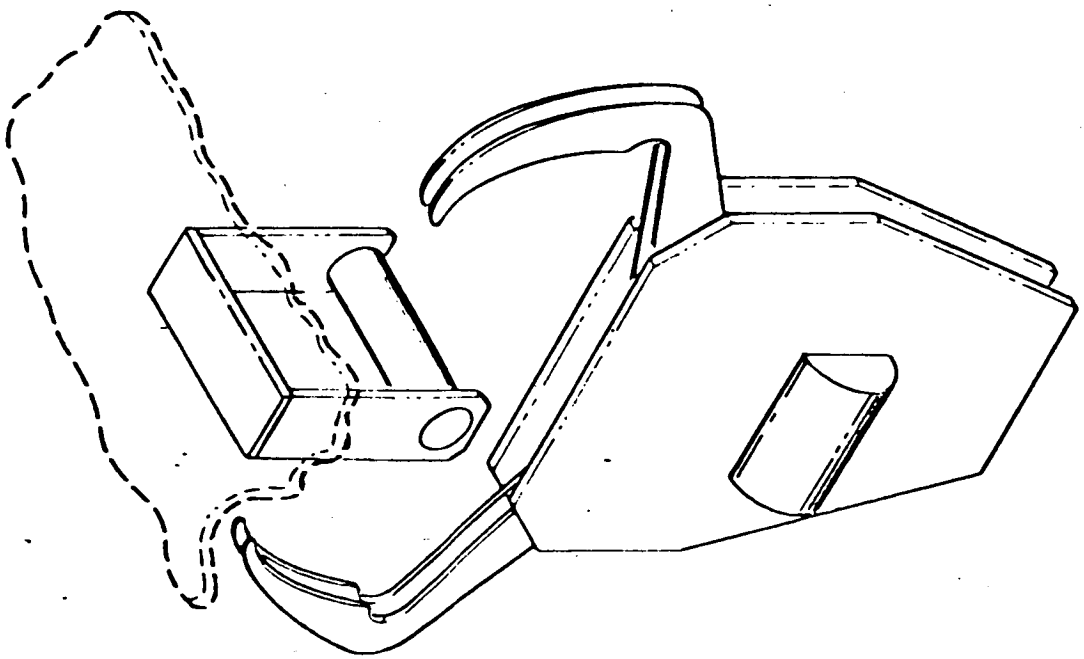
ALL RUNS CONDUCTED WITH RANDOM CHASE VELOCITIES, CHASE POSITION, AND TARGET ATTITUDE.

ED4582

TMS RF COMMUNICATIONS LINKS







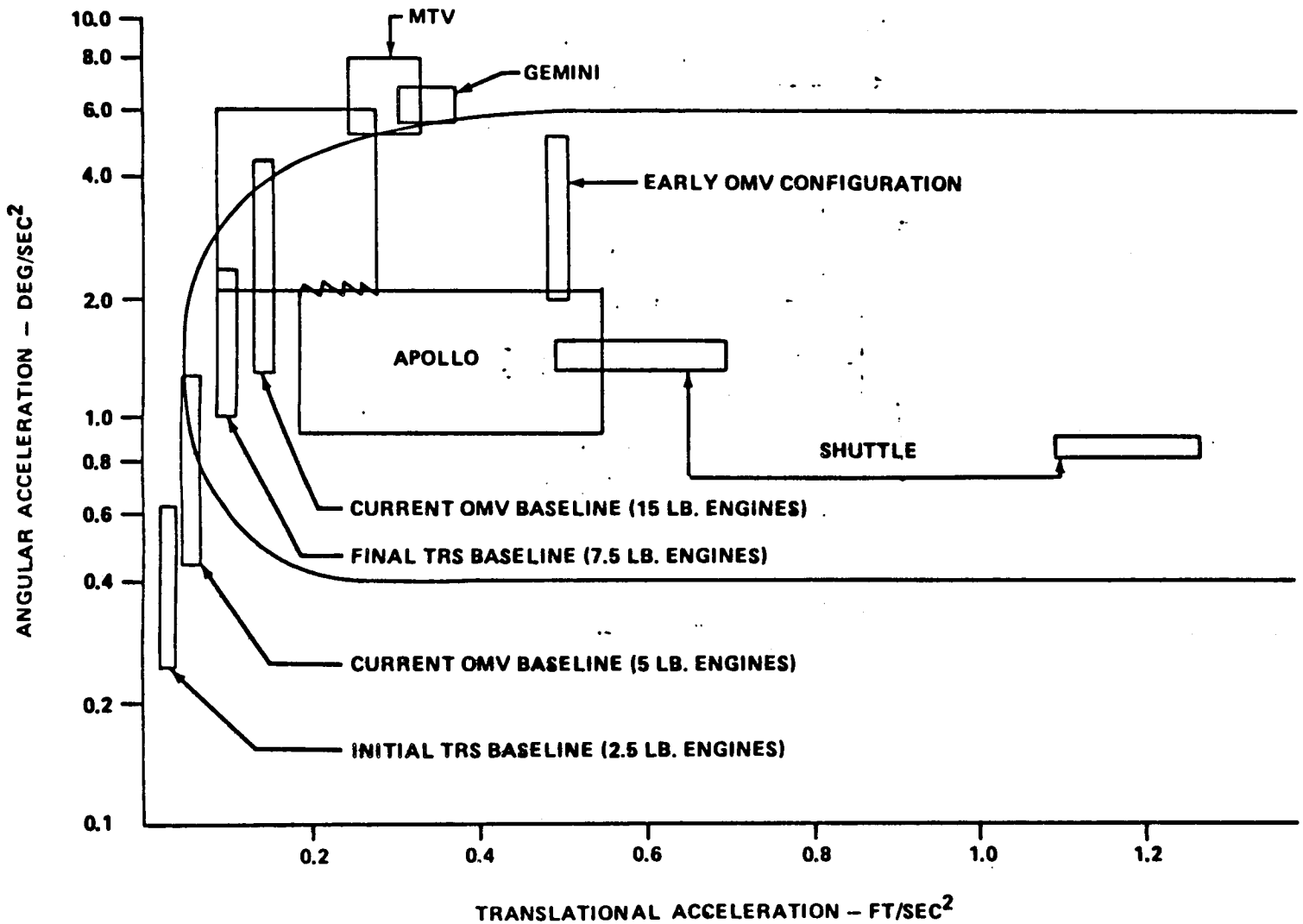
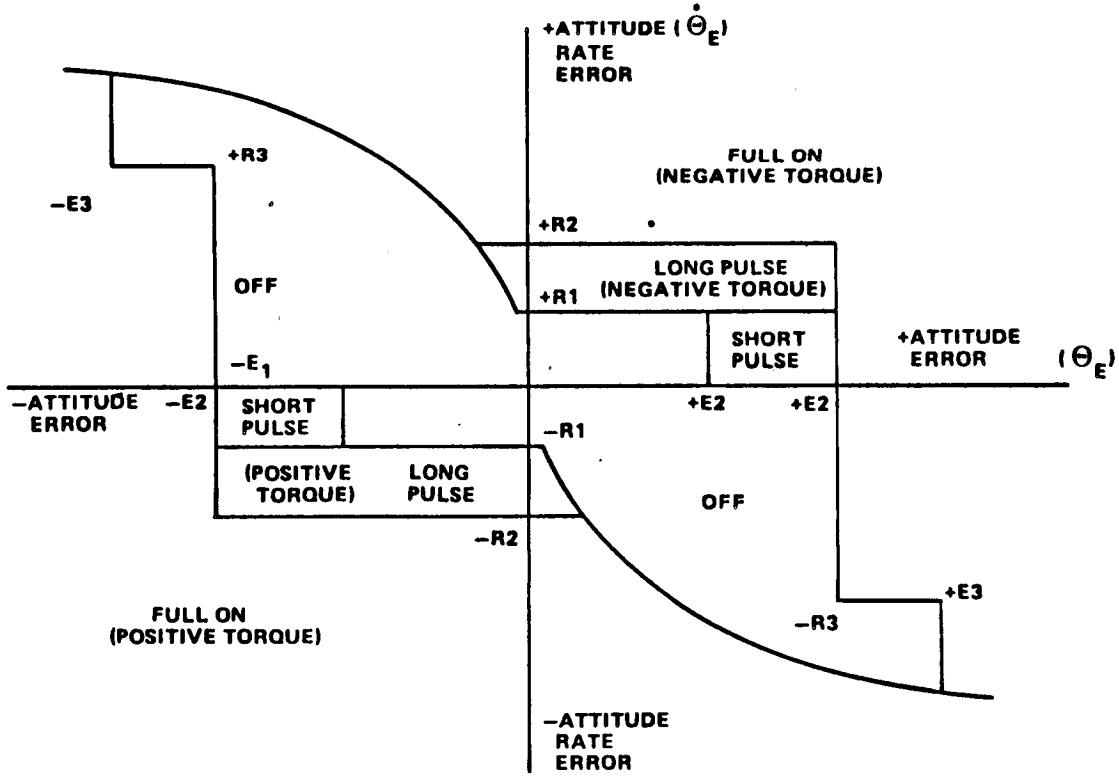
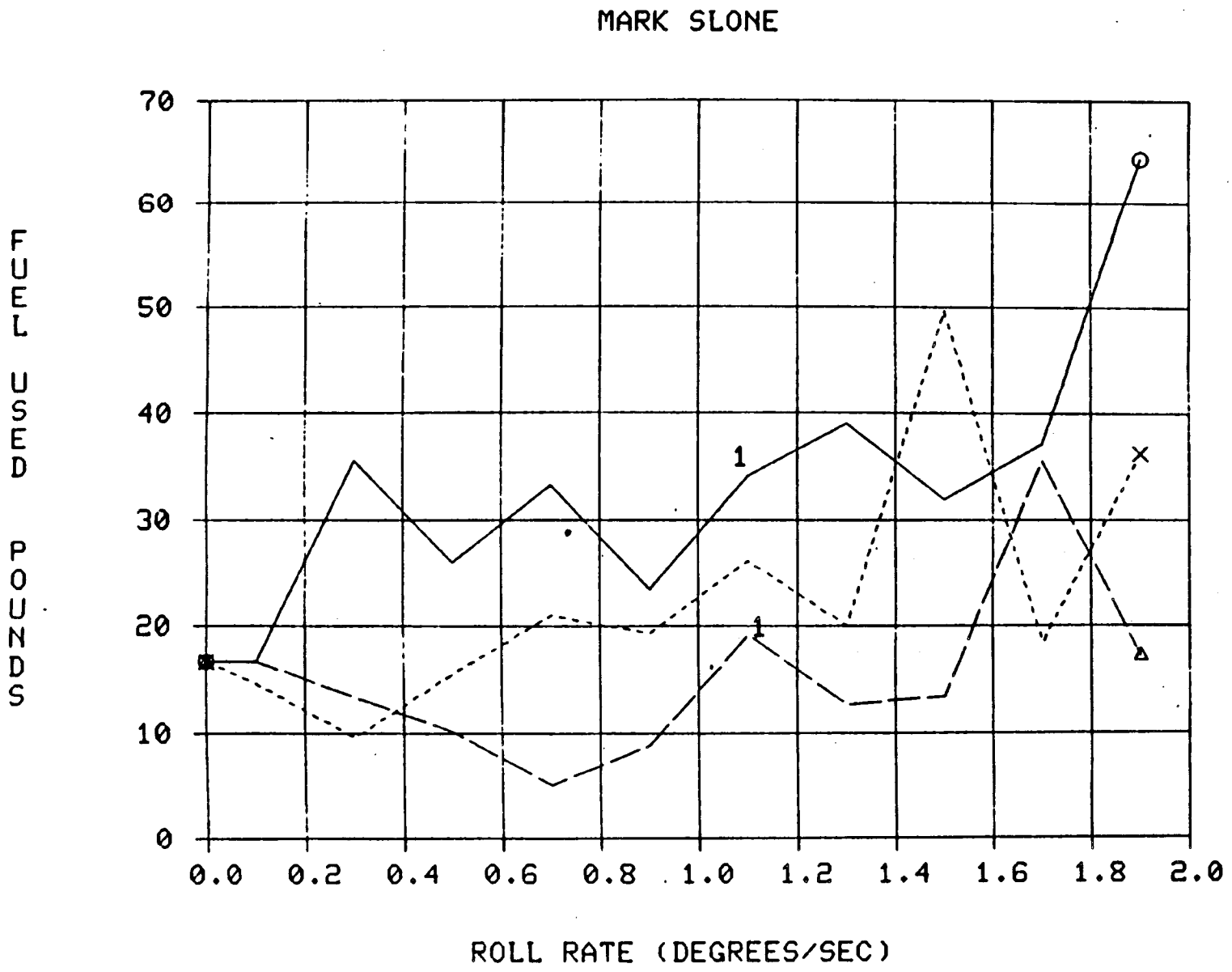

MTV
GEMINI
EARLY OMV CONFIGURATION
APOLLO
SHUTTLE
CURRENT OMV BASELINE (15 LB. ENGINES)
FINAL TRS BASELINE (7.5 LB. ENGINES)
CURRENT OMV BASELINE (5 LB. ENGINES)
INITIAL TRS BASELINE (2.5 LB. ENGINES)
ANGULAR ACCELERATION – DEG/SEC²
10.0
8.0
6.0
4.0
2.0
1.0
0.8
0.6
0.4
0.2
0.1
0.2
0.4
0.6
0.8
1.0
1.2
TRANSLATIONAL ACCELERATION – FT/SEC²

FIGURE 2

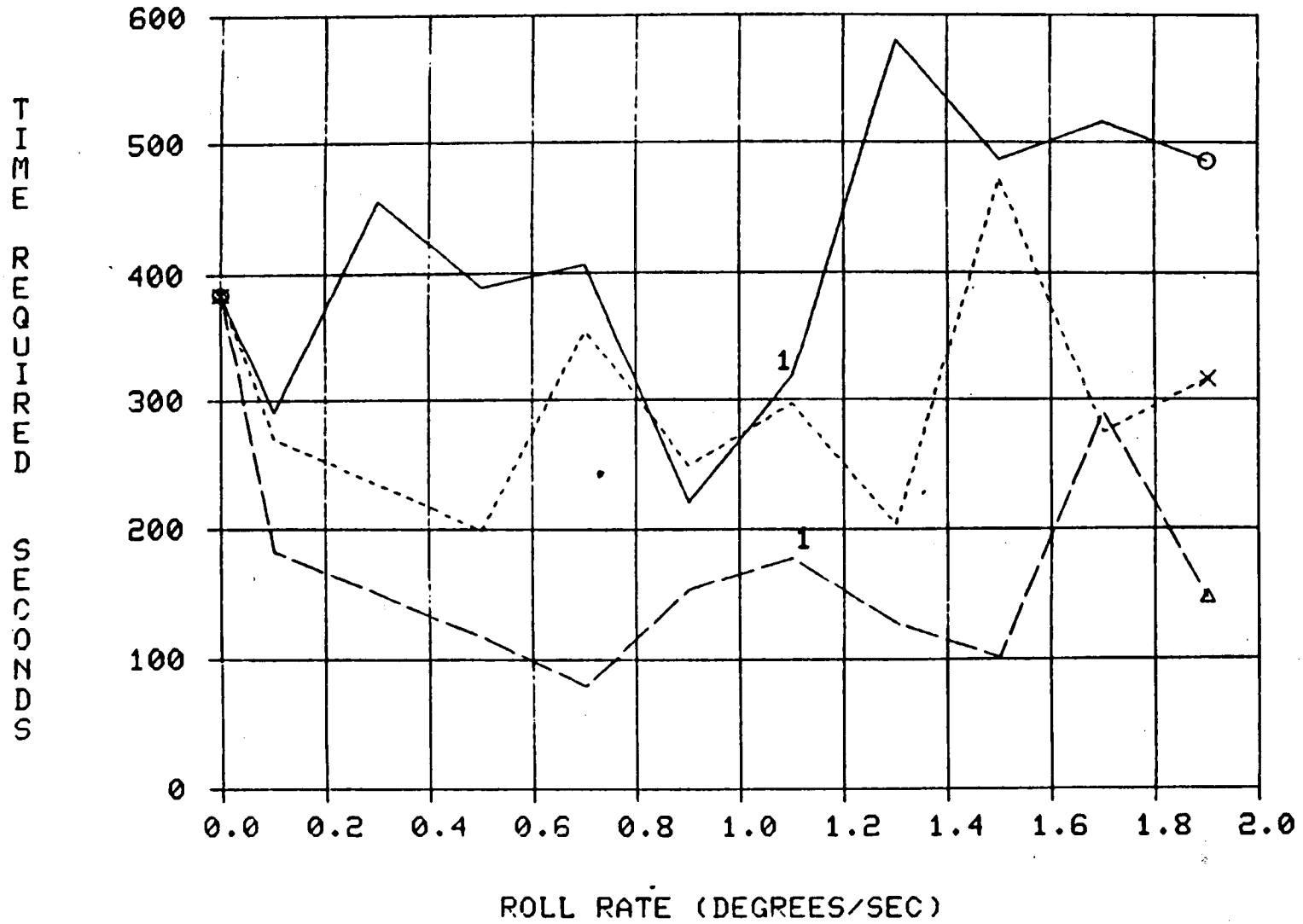
PHASE PLANE LOGIC DIAGRAM

$$\Theta_E = \frac{(\dot{\Theta}_E)^2}{C}$$

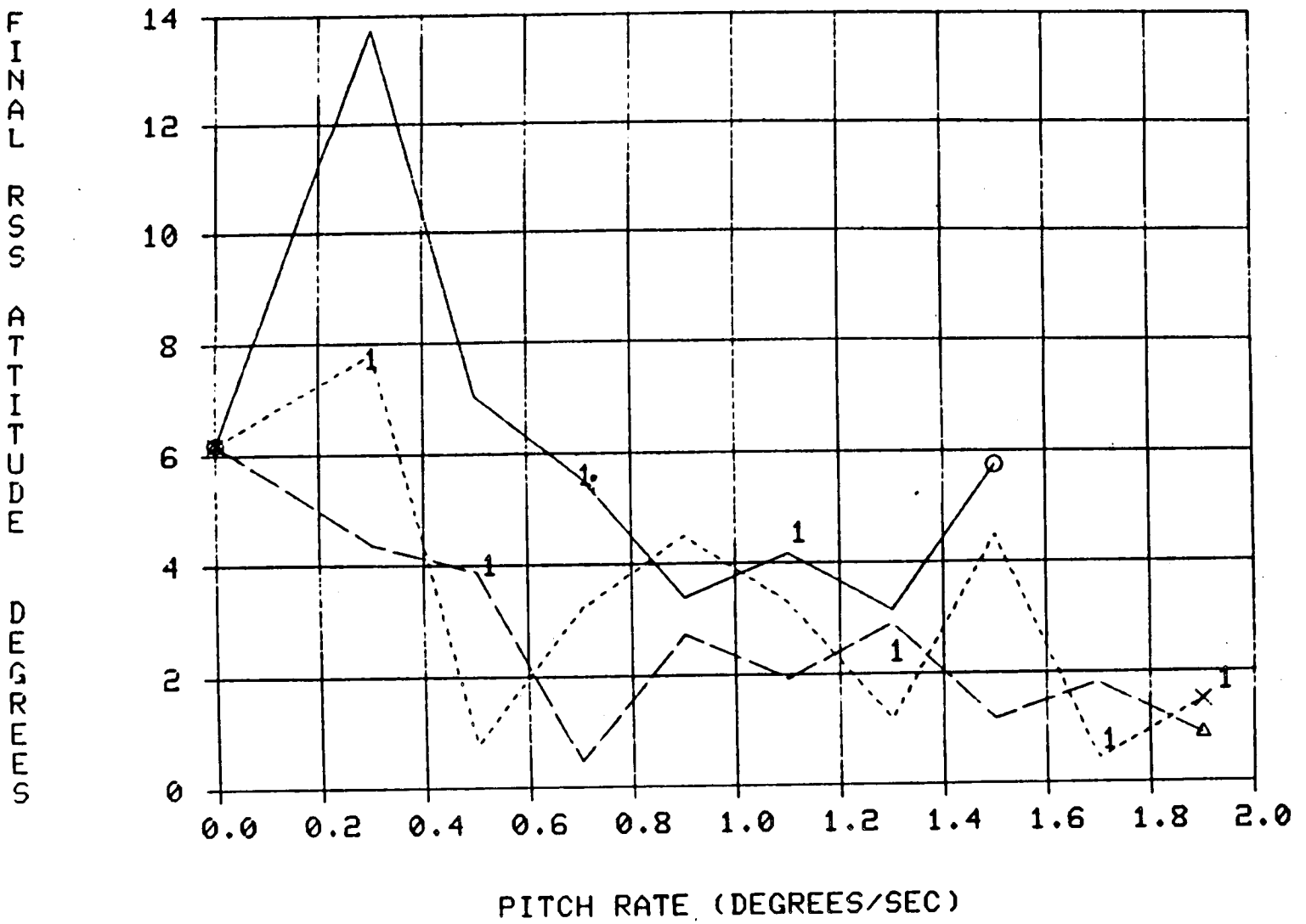



MARK SLONE
FUEL USED POUNDS
70
60
50
40
30
20
10
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
ROLL RATE (DEGREES/SEC)
1
1

MARK SLONE


600
500
400
300
200
100
0
TIME REQUIRED SECONDS
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
ROLL RATE (DEGREES/SEC)
1
1

JOHN SHARKEY



ORIGINALS FOR

Pages 9-137 Thru 9-139

ARE NOT AVAILABLE

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MISSION FRAME (*)

1- automatic RVD is envisaged for future space operations such as assembly, retrieval, servicing, maintenance and repair

2- a demonstration mission using EURECA as target is envisaged for the beginning of the next decade. Sun pointing spacecraft / 28.5° inclined orbit.

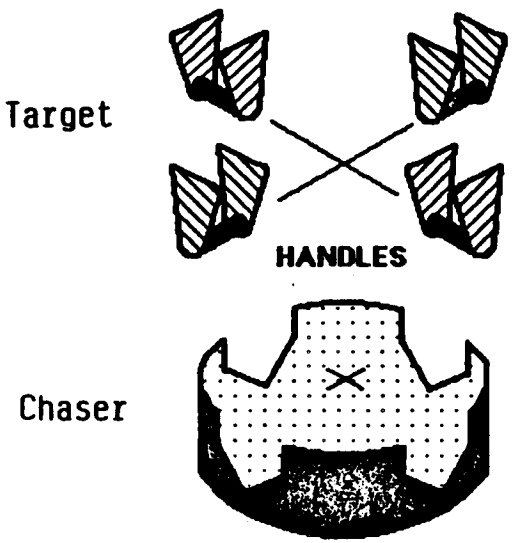
3- Europe has selected a very low impact docking with high accuracy relative position control prior to mechanism activation.

(*) see relevant papers presented by W.FEHSE/ESA and P.NATENBRUK/MBB-ERNO in session 8.

DOCKING CONCEPT

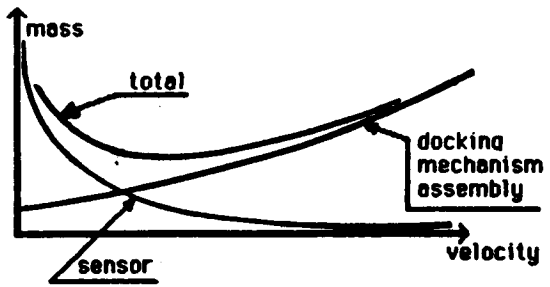
- low impact : velocity 5mm/s to 1cm/s
- small positioning error
  position <5cm
  angles <1deg.

MULTIPOINT ATTACHMENT DEVICE

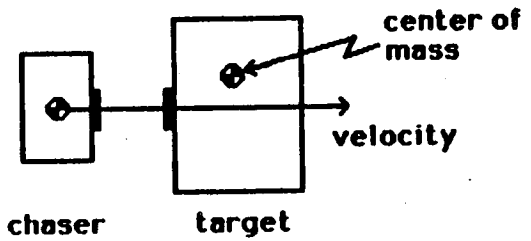


KEY CHOICE ELEMENTS

- mass



- momentum



  - composite angular rates after contact
  - loss of pointing/mission interrupt

- structural impact

SIMULATION OF THE LAST METERS OF APPROACH

GOALS :

- demonstrate that the guidance & control performance required for low velocity docking is achievable
- assess the relevant impact on the spacecraft systems and on the approach strategy.

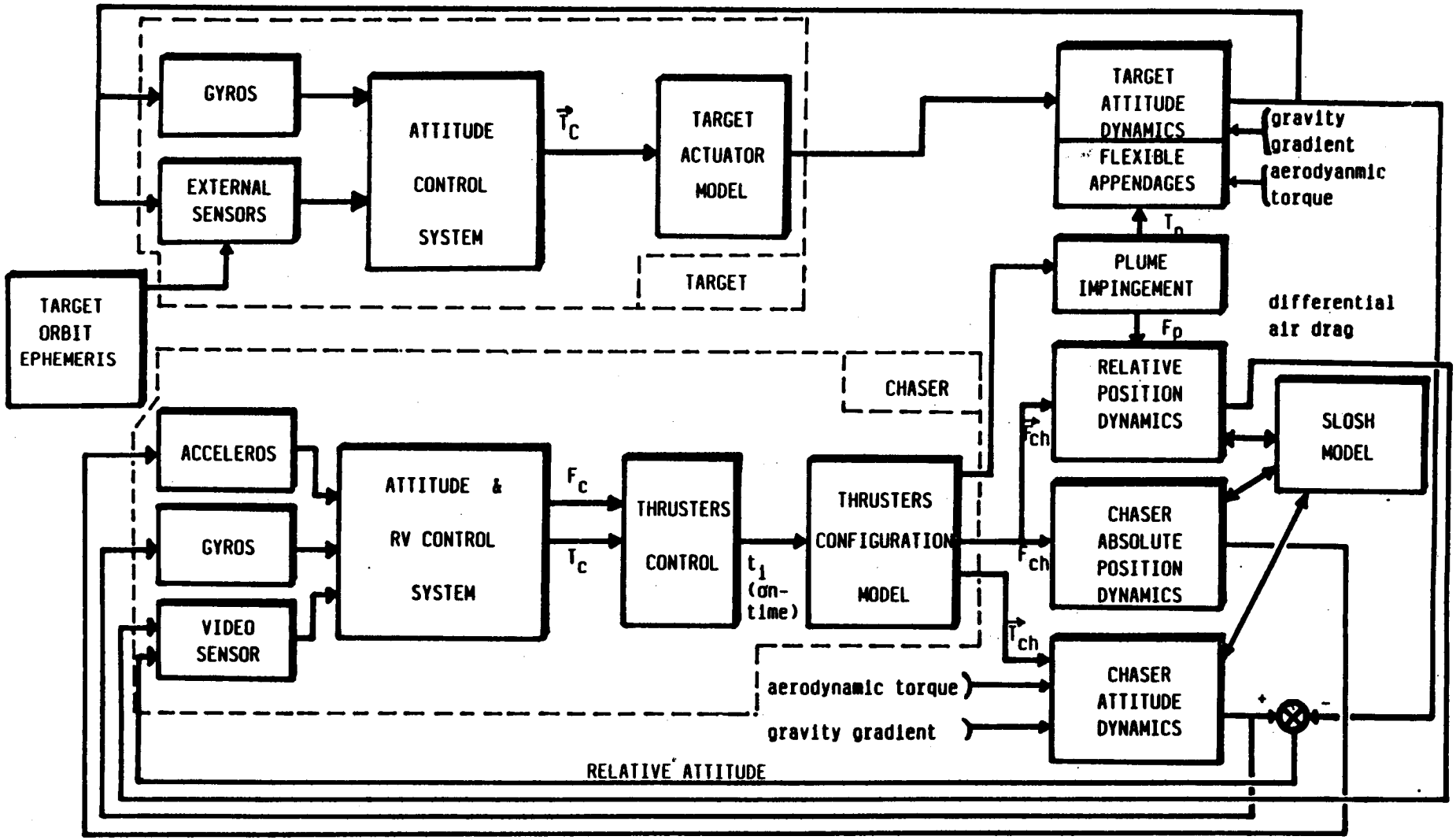
PROBLEMS :

- to demonstrate the high performance of the system, it is necessary to model :

  . all sources of disturbances that affect the relative motion :
    - flexibility of s/c
    - propellant slosh
    - differential drag
    - plume impingement of chaser thrusters
    - gravity gradient forces/torques
    - aerodynamic torques

  . the on-board equipments and control systems including delays, noises, sample rates and non-linearities.

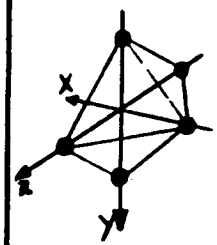
SIMULATION BLOCK DIAGRAMME



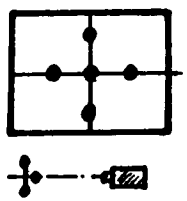
SENSOR CONCEPT (*)

PRINCIPLE : video sensor based on image analysis of a determined pattern on the target.

6-DOF MEASUREMENT : use a 5-DOTS pyramidal pattern



PATTERN SHAPE



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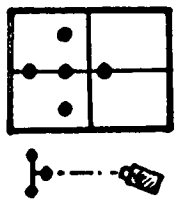
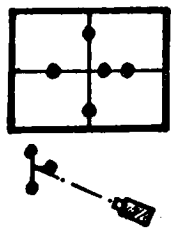
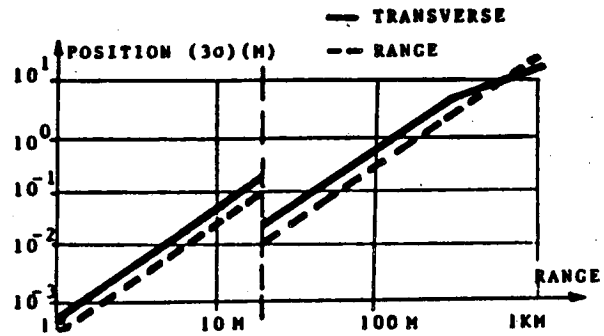
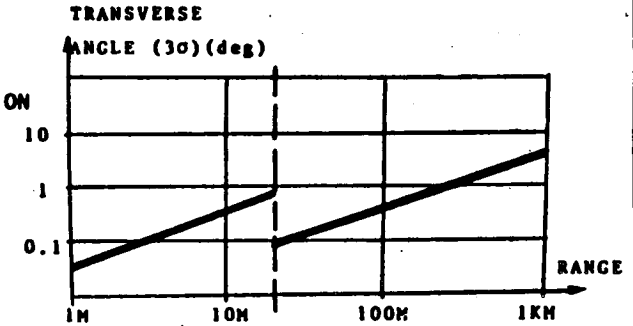


ANGULAR ERROR



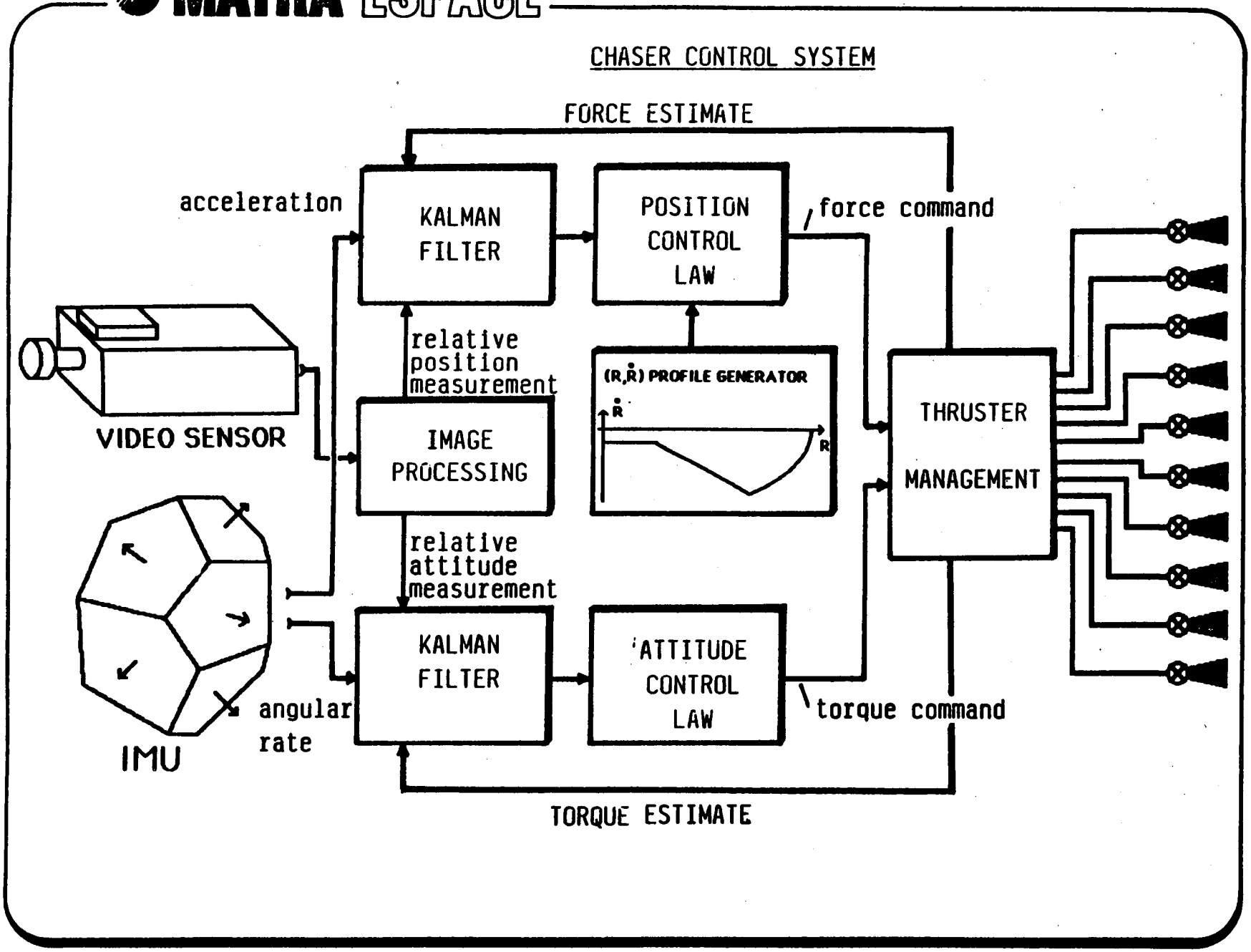
ANGULAR AND POSITION ERROR





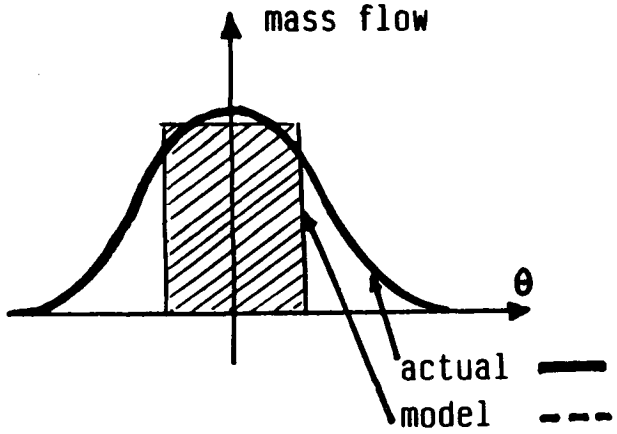
MODEL : - computation of each dot image
- quantizing and noise due to detector and dot barycenter processing.

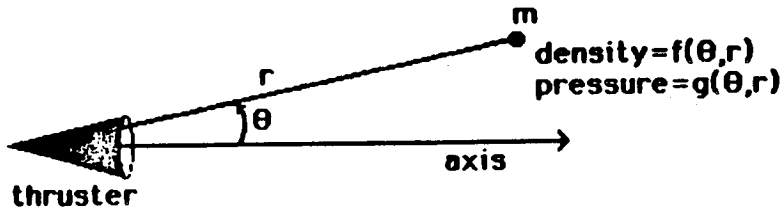
(*) detailed design is presented by B.KUNKEL/MBB-ERNO in session 6.

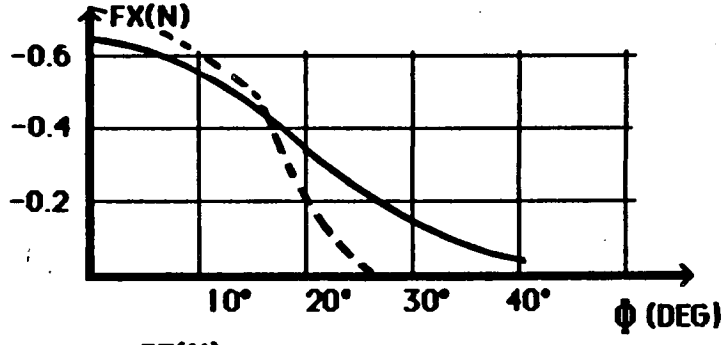

CHASER CONTROL SYSTEM
FORCE ESTIMATE
acceleration
KALMAN FILTER
POSITION CONTROL LAW
force command
relative position measurement
(R,Ṙ) PROFILE GENERATOR
Ṙ
R
VIDEO SENSOR
IMAGE PROCESSING
THRUSTER MANAGEMENT
relative attitude measurement
KALMAN FILTER
ATTITUDE CONTROL LAW
torque command
angular rate
IMU
TORQUE ESTIMATE

PLUME IMPINGEMENT MODEL

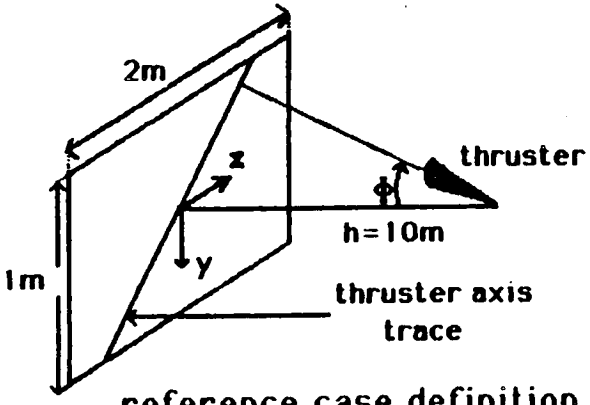
- simulate a gas jet for each thruster when actuated
- simplified by a cone of constant density repartition.



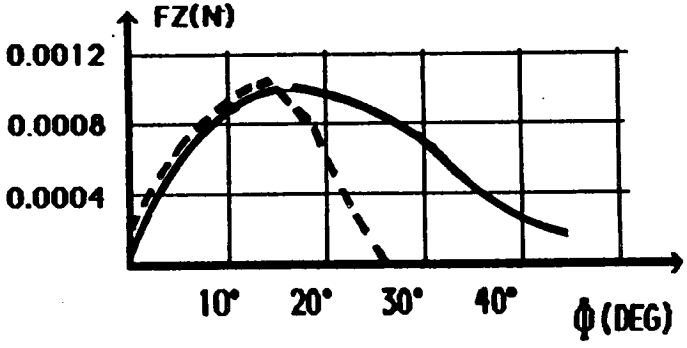




VALIDATION :

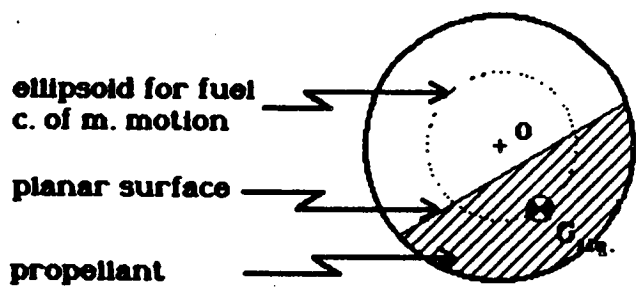


reference case definition



PROPELLANT SLOSH MODEL

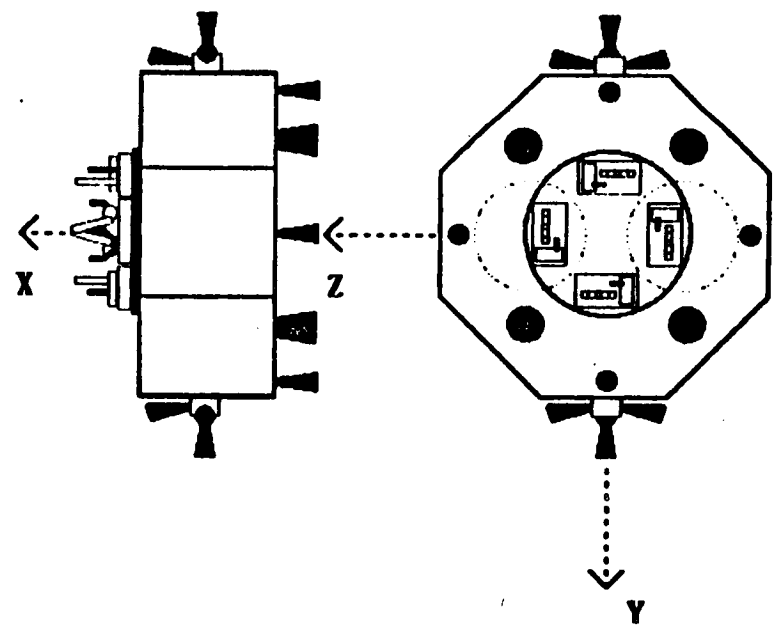
- N ellipsoidal tanks
- viscosity and surface tension forces
- only the fuel center of mass motion is modeled (and not the surface modes)



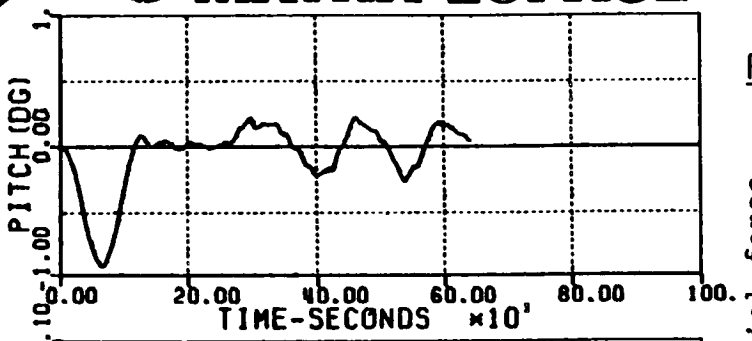
THRUSTER CONFIGURATION AND CONTROL

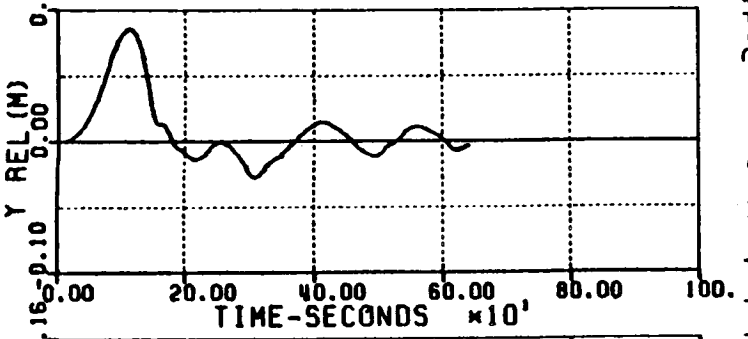
- minimum on-time
- no delay
- pulse width modulation
- 1N cold gas thrusters

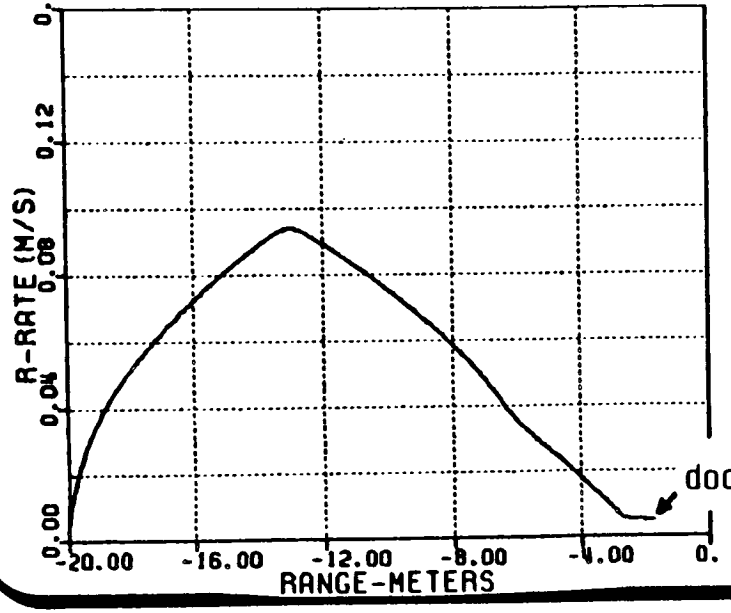
CONFIGURATION

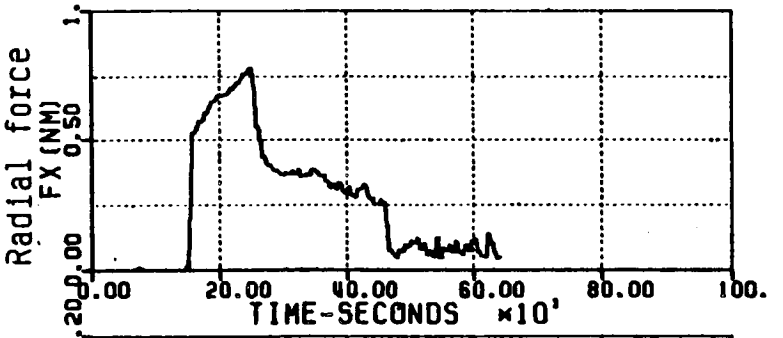


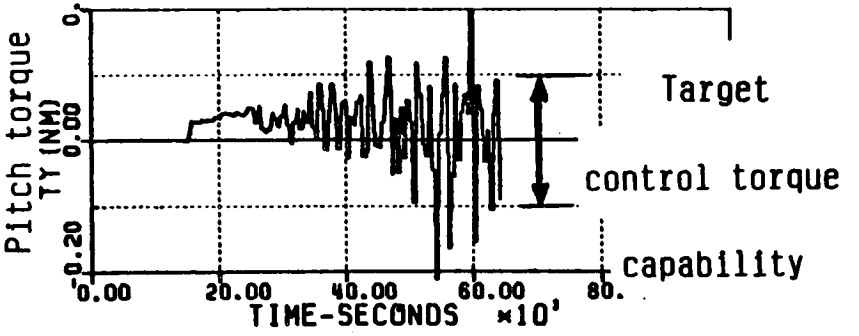
RESULTS







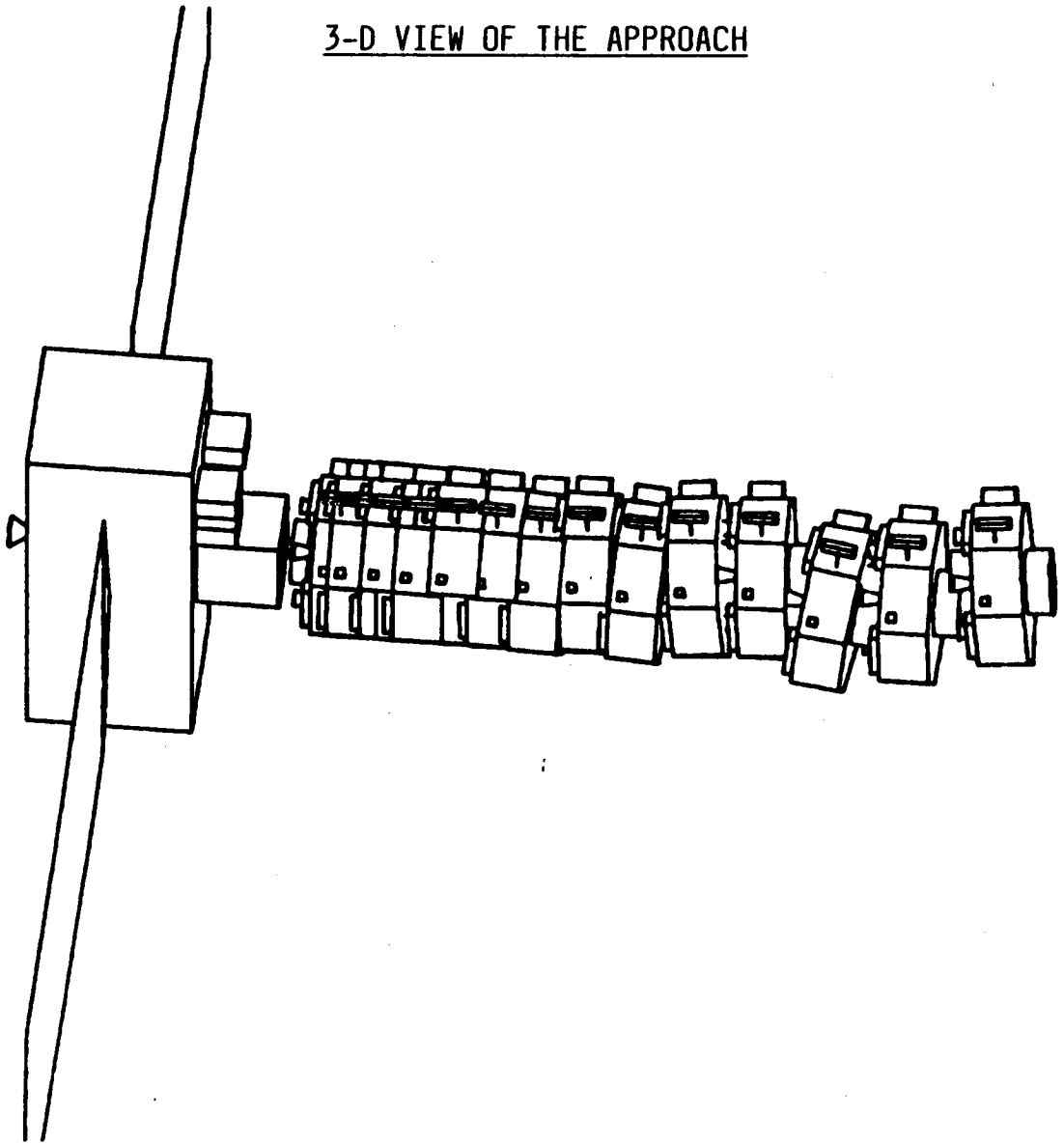




PLUME IMPINGEMENT

9-148

3-D VIEW OF THE APPROACH



PERFORMANCES / CONCLUSIONS

1- analysis of the last meters of approach requires a very sophisticated simulation

2- achievable accuracy are typically
- 2 cm (transverse position)
- 0.25° (transverse angle)

and are fully compatible with the low impact docking concept

3- care should be taken w.r.t. plume impingement on the target which may :
- increase the control gain along the docking axis
- induce perturbing torques higher than the target control capability

4- propellant slosh has not a dominant effect when :

$$\frac{\text{fuel mass}}{\text{chaser mass}} < \frac{200\ \text{kg}}{3000\ \text{kg}}$$

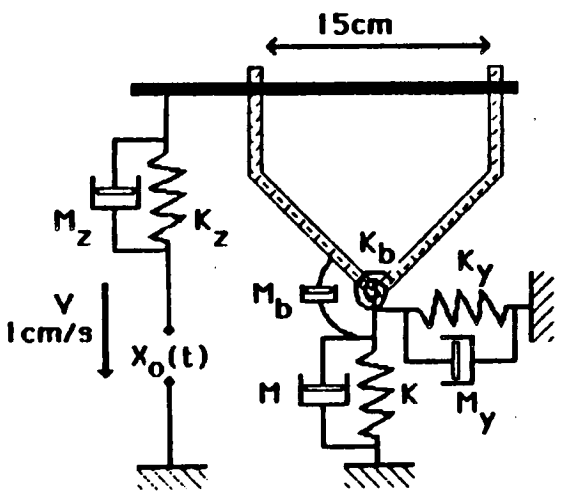
DOCKING PHASE

SIMULATION

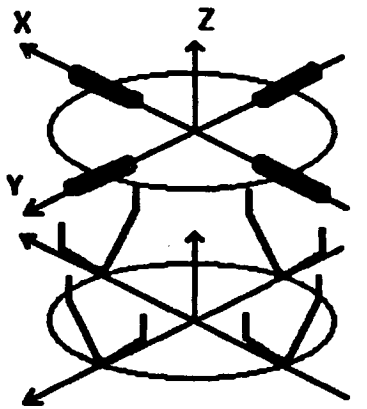
9451

DOCKING PHASE SIMULATION

- 3-axis (6-DOF) simulation of the vee concept
  - . 4 latches on the chaser
  - . 4 handles on the target.



V and latch model



DOCKING INTERFACE MODEL

GOALS / PROBLEMS

GOALS :

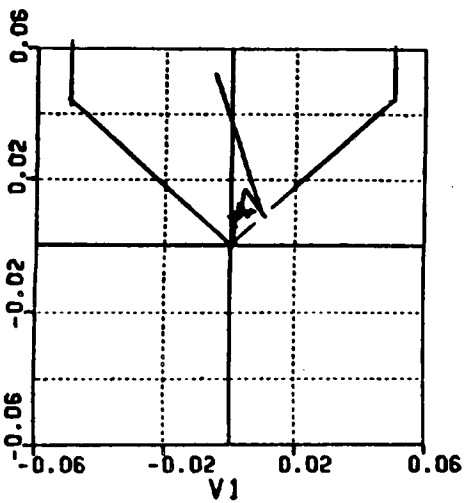
- evaluate loads during the capture and hardlocking on :
  . the S/C bodies
  . the latches
- analyse the relative motion during capture and latching.

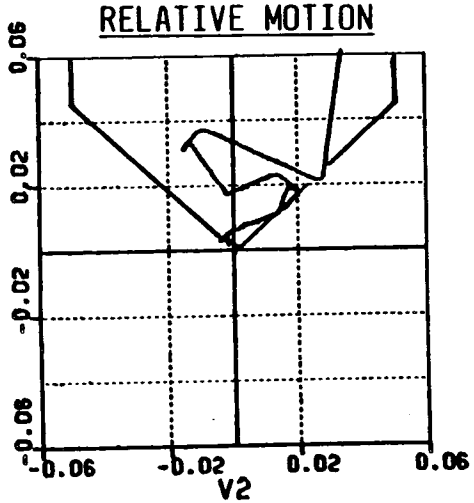
PROBLEMS :

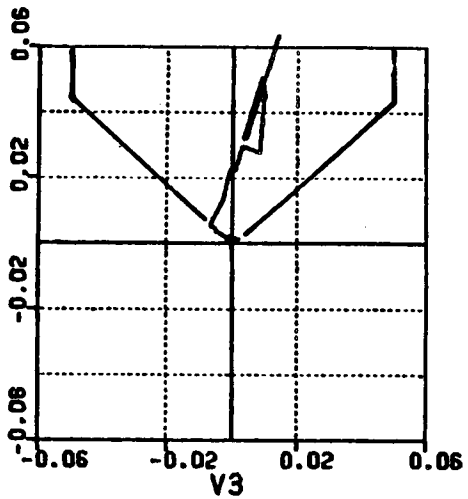
- dry friction introduces non-linearities in the equations and numerical problems due to time sampling
- motion equations structure depends on contact conditions when any degree of freedom is fixed :
- this leads to :
  . model flexibility at key points to prevent from D.O.F. lock
  . to use high sampling rates (E.G. 5 millisecond).

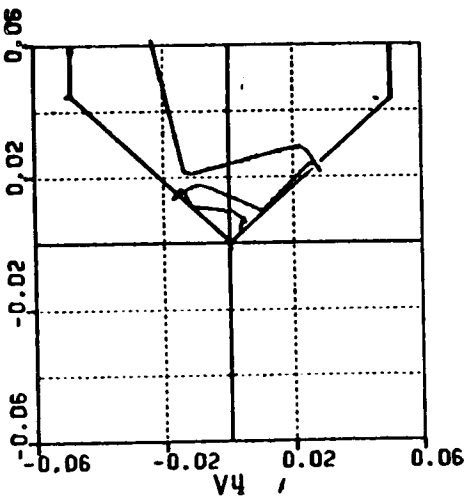
ILLUSTRATION OF OUTPUTS

RELATIVE MOTION



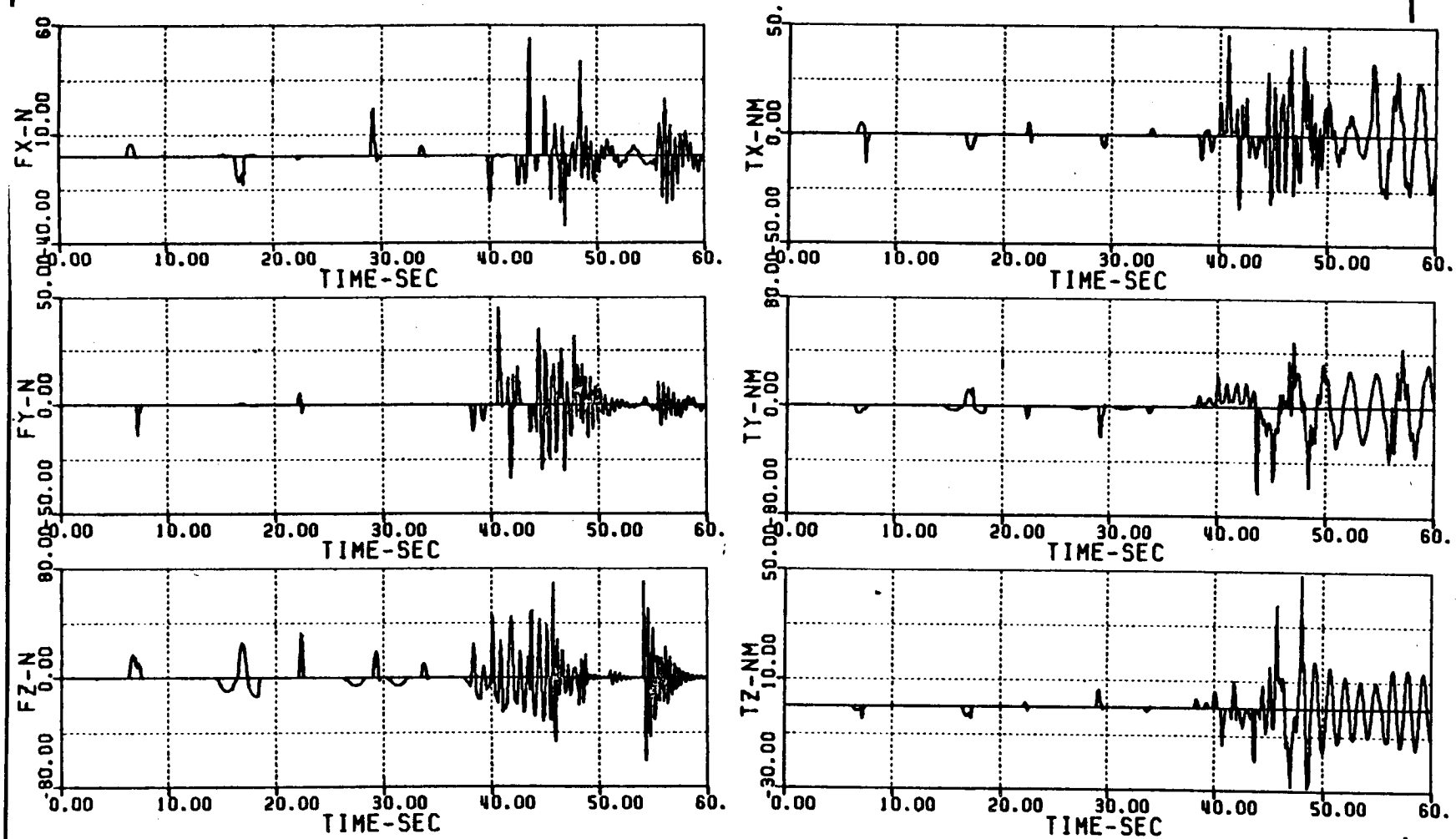






MATRA ESPACE

ILLUSTRATION OF OUPUTS
FORCES/TORQUES ON CHASER S/C



9-155

CONCLUSIONS / RECOMMENDATIONS

- a computer simulation is needed to :
  1 - evaluate the loads during the docking process. Internal loads are used for mechanism design. Inter-S/C loads are used for motion and docking port structure analysis

  2- check the correctness of the design for capture and latching functions

  3- dimension the spring and damping characteristics.

- future work :
  . include hinge locking capability
  . extend contact model to non-plane surfaces
  . extend capability to robotic manipulation : grasping, insertion, ...

SESSION 10 - OPTICAL SENSORS

10-1. "Smart Sensors for Rendezvous and Proximity Operations" - Roger Breckenridge/NASA LaRC

10-2. "Optical Shuttle Sensors and Television Proximity System Overview" - Olin Graham/NASA JSC

10-3. "Intensified CCD Cameras for Low Light Level Applications" - Kenneth Hoagland/Fairchild Weston Systems

10-4. "Advanced Visible and Infrared Image Sensors" - Walter Kosonocky/RCA Laboratories

10-5. Integrated Sensing/Processing for Autonomous Operations" - D. Jobson/LaRC

10-6. "Advanced Semiconductor/Solid-State Laser Sources for Ranging and Illumination" - Donald Carlin/RCA Laboratories

10-7. "SHAPES Laser Rangefinder and New Concepts for a Rendezvous and Proximity Operations Senbsor" - E. Tubbs, J. McLauchlan, and N. Nerheim/JPL

SMART SENSORS FOR RENDEZVOUS AND PROXIMITY OPERATIONS

Roger A. Breckenridge

SMART SENSORS FOR RENDEZVOUS AND PROXIMITY OPERATIONS

ABSTRACT

This paper is an up-date of two papers on this topic in the 1980 time frame. It discusses the role of smart sensors in rendezvous and proximity operations. The meaning of smart sensor is discussed in conjunction with its desirable characteristics. The critical functions necessary for the realization of smart sensors are discussed. The impact of the development of smart sensors on future space missions such as the Space Station is addressed in terms of size, speed, and changes in onboard and ground-based central processing unit functions. Technology trends which will assist in the realization of smart sensors are also discussed.

10-3

DEFINITION OF SMART SENSOR

TAO, ET AL:	SMART SENSOR SYSTEMS - "SENSOR SYSTEMS WHICH CONTAIN BOTH SENSING AND SIGNAL PROCESSING CAPABILITIES. . ."
WIENER:	SMART SENSOR - "A SMART SENSOR MEASURES THE MOST APPROPRIATE QUANTITIES WITH THE REQUIRED ACCURACY AND EXTRACTS THE MAXIMUM AMOUNT OF INFORMATION FROM THOSE MEASUREMENTS."
BRECKENRIDGE AND HUSSON:	SMART SENSOR - "A SENSOR THAT, ACTING ALONE OR IN A SET, PERFORMS A COMBINATION OF SENSORY AND DATA/INFORMATION PROCESSING FUNCTIONS WITH A SINGLE APPARATUS."

10-4

DEFINITION OF SMART SENSOR

Three separate definitions as perceived by three different authors have appeared in the literature. These definitions are shown in the accompanying figure. Tao, et al, view smart sensor systems as sensor systems which contain both sensing and signal processing capabilities. Wiener defines a smart sensor to be a sensor which measures the most appropriate quantities with the required accuracy and extracts the maximum amount of information from those measurements. Breckenridge and Husson defined a smart sensor to be a sensor that, acting alone or in a set, performs a combination of sensory and data/information processing functions within a single apparatus. The definitions agree that at least signal processing is integrated with the sensory capability. The second two definitions actually imply that information processing functions are integrated with the sensing functions. In this paper, it will be assumed that more than signal processing is required to label a sensor "smart." Also, the terms smart sensor and integrated sensor can be used interchangeably if the sensor has an integrated information processing capability.

10-5

DESIRABLE CHARACTERISTICS OF A SMART SENSOR – BRECKENRIDGE AND HUSSON

- INTRODUCES NO ANOMALIES INTO THE DATA.
- PERFORMS ANALYTICAL AND STATISTICAL CALCULATIONS.
- PERFORMS ALL OPERATIONS IN THE SIMPLEST POSSIBLE FORM.
- HANDLES NEW DATA ACQUISITION AND PROCESSING SITUATIONS.
- INTERACTS WITH OTHER SENSORS.
- ADJUSTS TO DIFFERENT ENVIRONMENTAL CONDITIONS.
- EXTRACTS INFORMATION IN A USEFUL FORM.
- MAKES DECISIONS.

DESIRABLE CHARACTERISTICS OF A SMART SENSOR

Breckenridge and Husson examined the definition of a smart sensor from the standpoint of its desirable characteristics. The characteristics are listed on the accompanying figure. The smart sensor should introduce no anomalies into the data which are characteristic of the sensor itself. A smart sensor should be able to perform calculations, analytical and/or statistical, to extract information. It should be able to perform all operations in the simplest possible form to insure optimum performance. A smart sensor should handle new data acquisition and processing situations through reconfiguration of itself. It should be able to interact with other sensors to provide or receive data/information. It should be able to adjust to different environmental conditions. A smart sensor should be able to extract information in a form readily usable by a user or system. It should be able to make decisions such as whether certain data should be edited or whether information should be transmitted. Not all of these characteristics are necessary for a sensor to be smart, but the presence of several of them justifies the use of the term.

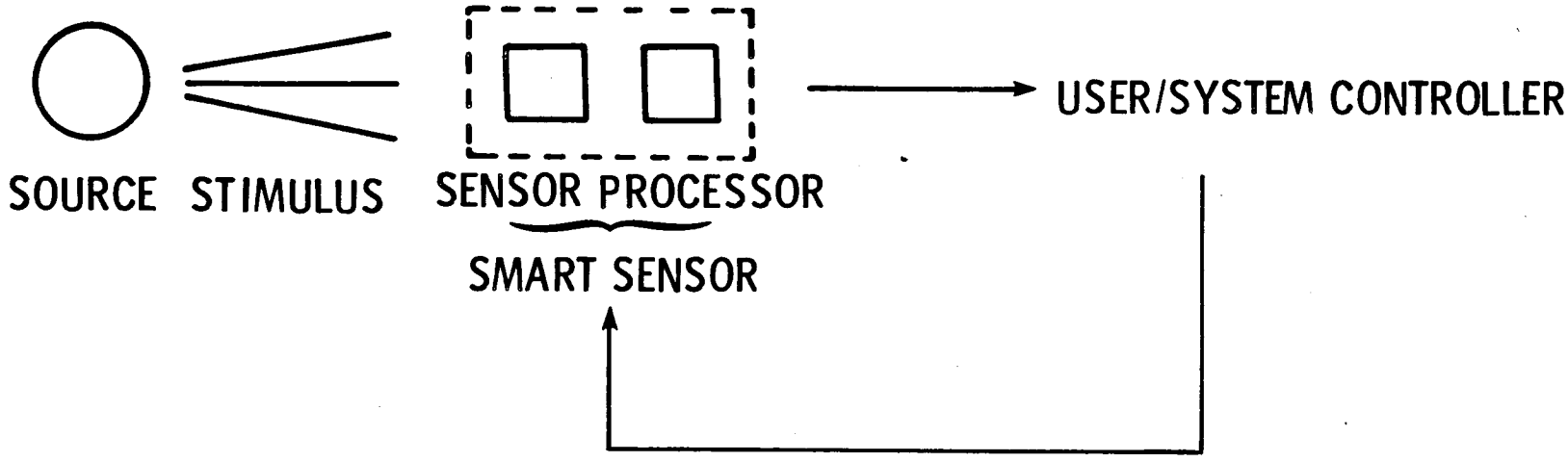
FUNCTIONS NECESSARY FOR SMART SENSORS

- Incorporates data processing as an integral function
- Performs automatic calibration
- Performs automatic compensation
- Possesses sets of algorithms
- Must be able to reconfigure itself
- Must have at least a limited memory capability

FUNCTIONS NECESSARY FOR SMART SENSORS

A certain number of functions are necessary in the development of smart sensors. Data processing must be incorporated as an integral function of the smart sensor. Dynamic calibration and compensation of the sensor, which are performed automatically, are required. Sets of algorithms must be available in the sensor so that analytical and statistical calculations can be performed at the sensor. These sets of algorithms could be stored in memory and implemented electronically as a part of the sensor. The smart sensor must be able to reconfigure itself to insure the required flexibility for different data acquisition situations and for various environmental conditions. At least a limited memory capability is required to store algorithms, compensation parameters, and data before it is processed.

CONCEPTUAL DIAGRAM OF REMOTE SENSING BY A SMART SENSOR



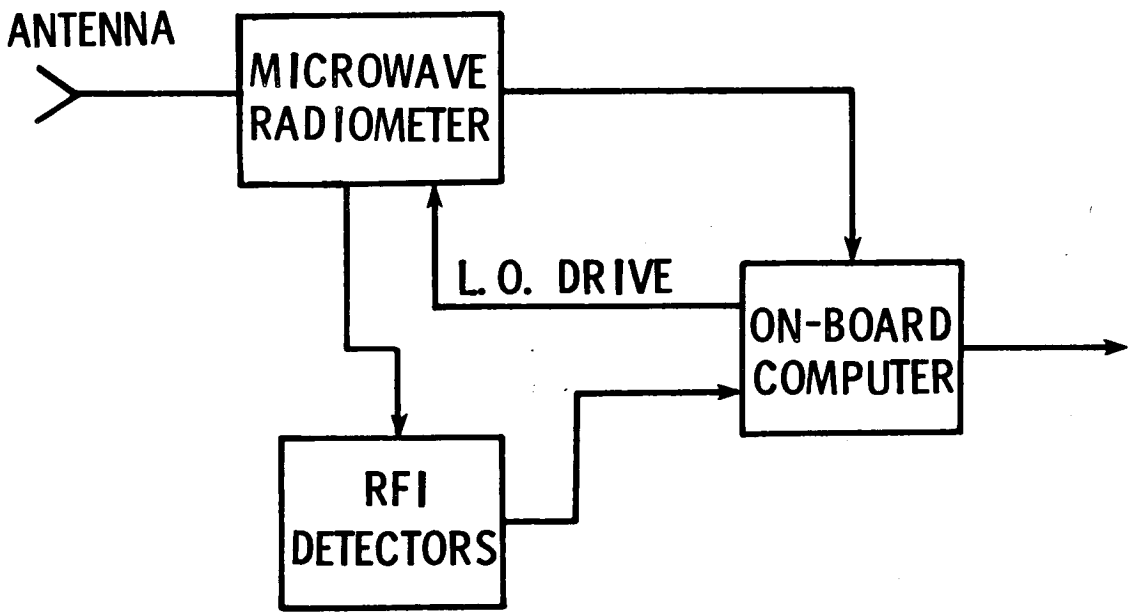
10-10

CONCEPTUAL DIAGRAM OF REMOTE SENSING BY A SMART SENSOR

In the accompanying figure, a conceptual diagram of remote sensing by a smart sensor is shown. A physical entity or source generates a physical measurable. This physical measurable is transmitted to the sensor portion of the smart sensor. This transmitted physical measurable is called a stimulus. The stimulus interacts with the sensor to produce measured quantities, that is, the sensor acquires data. The processor portion of the smart sensor performs data processing and/or information extraction. The smart sensor then transmits information or, in many instances, processed data to the user/system controller. A feedback loop between the user/system controller and the smart sensor can exist which permits the user/system controller to affect the operation of either the sensor or the processor portion of the smart sensor.

"SMART" MICROWAVE RADIOMETER SYSTEM WITH RFI AVOIDANCE

(BLUME, ET AL, 1978)



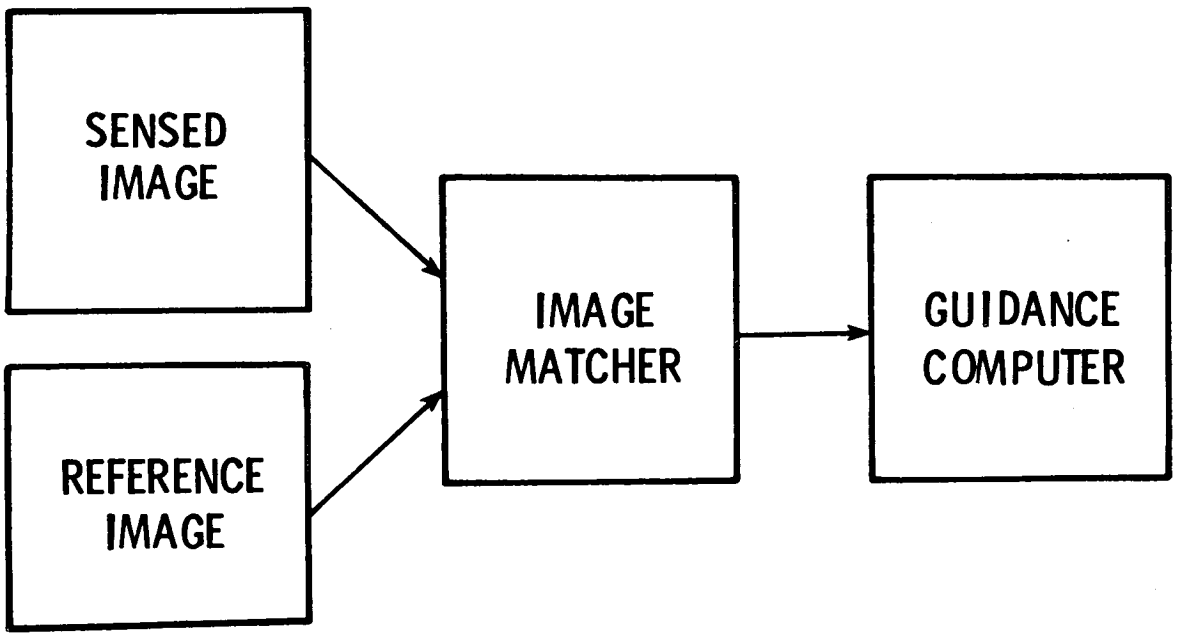
"SMART" MICROWAVE RADIOMETER SYSTEM WITH RFI AVOIDANCE

An excellent example of a smart sensor is shown in the accompanying figure. This smart sensor concept was shown at a conference on smart sensors held at the NASA Langley Research Center in November 1978. In this concept, radio frequency signals interferring with the sensing of a microwave radiometer can be avoided by frequency shifting. By detecting interference signals with the onboard RFI detectors, the onboard computer can process this information and shift the frequency or frequency band at which the radiometer is performing measurements and thereby avoid the interference.

10-13

IMAGING SENSOR SYSTEM FOR TERMINAL HOMING

(WIENER, 1979)



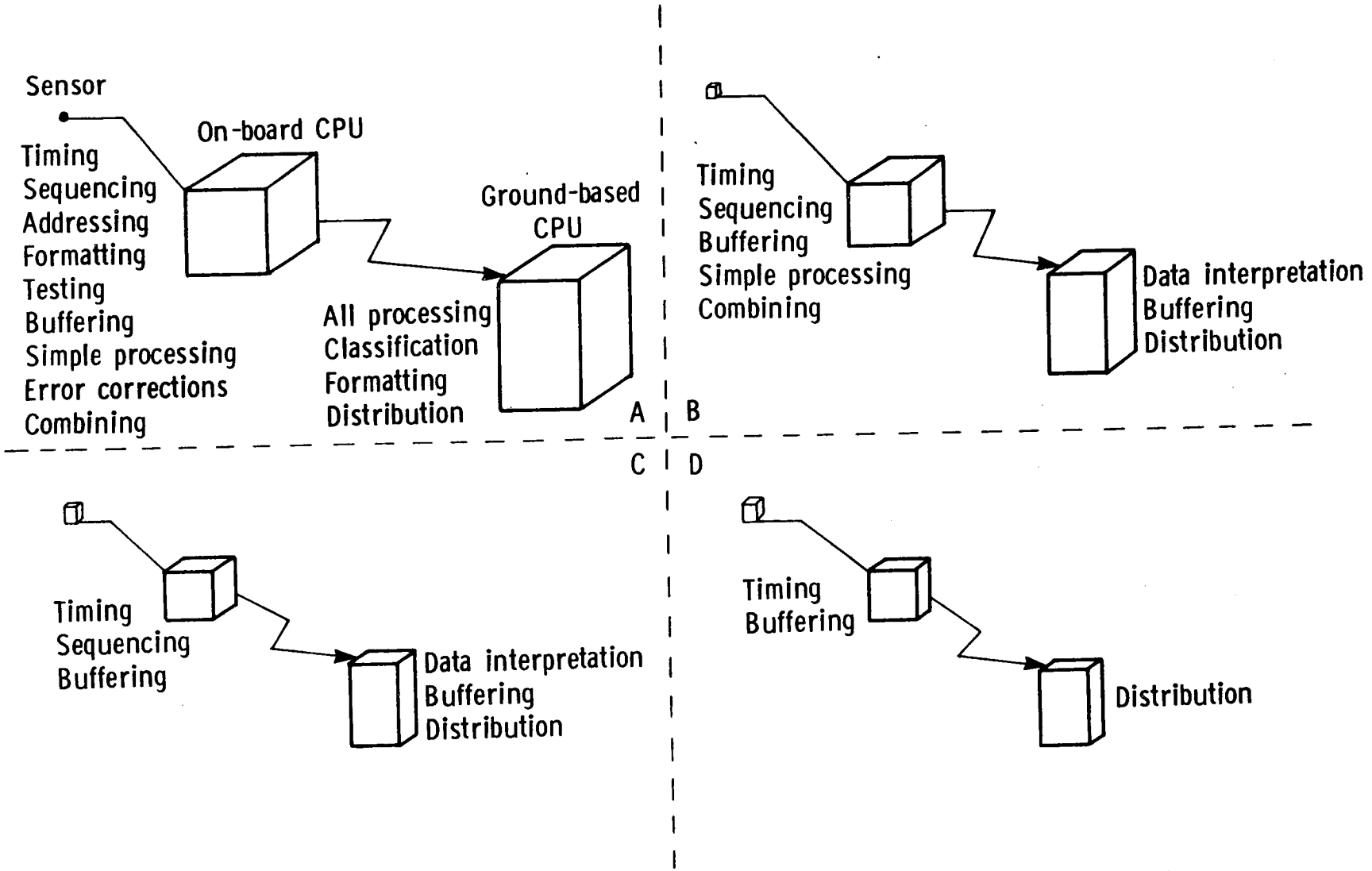
10-14

IMAGING SENSOR SYSTEM FOR TERMINAL HOMING

A second excellent example of a smart sensor was addressed at a smart sensors conference in 1979 in Washington, D.C. The sensor system concept is shown in the accompanying figure. In this concept a sensed image is compared with a reference image in an image matcher to determine any difference in viewing position of the sensed image from the reference image. This difference is transmitted to the guidance computer which issues commands to return the vehicle to its original trajectory or correct its trajectory.

10-15

Sensor/ CPU relationships as modified by smart sensor evolution.



SENSOR/CPU RELATIONSHIPS AS MODIFIED BY SMART SENSOR EVOLUTION

The accompanying figure demonstrates schematically the ramifications of smart sensor development on the size and function requirements of the onboard and ground-based central processing units (CPU's). Currently, nearly all significant processing takes place in the CPU, and the sensor need only meet requirements for accuracy and stability. For the whole set of sensor instrumentation for a space mission, the CPU costs are large because of the significant amount of calibration, raw data handling, and housekeeping that must be performed. Up to this point, the size of the ground-based processor relative to the onboard processor is large because of the requirement that all data processing be performed in the ground-based CPU except onboard housekeeping (see quadrant A). With the Space Staion comes the requirement for a significant amount of onboard processing. Reaching the goal in the quadrant D is based on transferring much of the data processing to the smart sensor itself. The smart sensor should constantly reduce the overhead burden in the onboard and ground-based CPU's through all of its evolutionary steps (A→B→C→D).

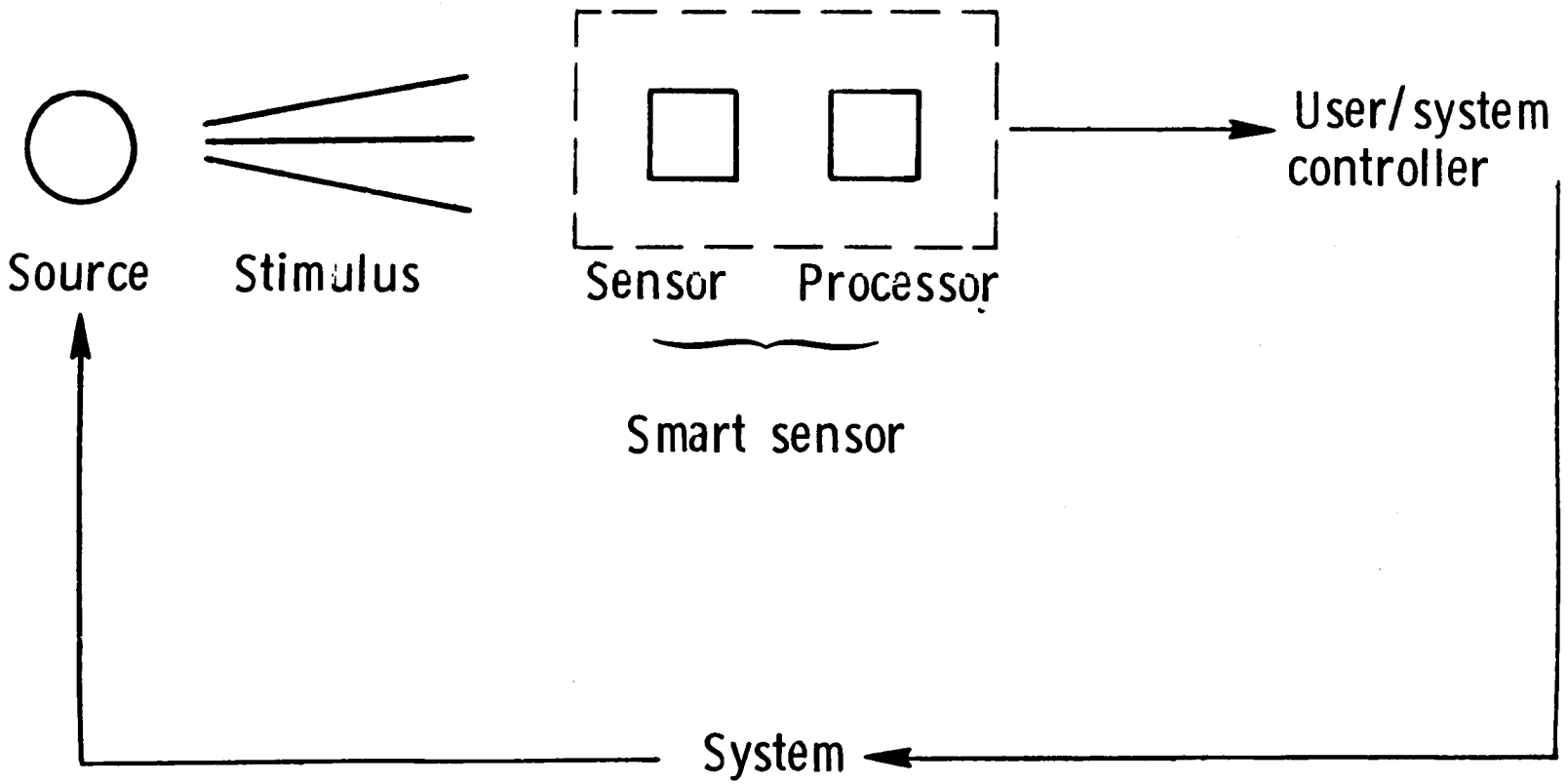
ADVANTAGES OF SMART SENSORS

- Allow onboard editing and decision making to reduce quantity of data to be processed
- Reduce volume of data to be managed
- Reduce data processing delay time significantly
- Increase speed of response of system(s) dependent upon smart sensor
- Allow multisensor interaction and changes in sensor configuration
- Provide information directly to the user instead of raw data

ADVANTAGES OF SMART SENSORS

The advantages of smart sensors, or integrated sensors, for rendezvous and proximity operations are addressed on the accompanying figure. Smart sensors permit onboard editing and decision making to reduce the quantity of data to be processed onboard the spacecraft or telemetered to the ground and processed. This reduces the volume of data to be managed by the data management system, onboard and from orbit to the ground. Data processing delay times will be reduced significantly which will increase the speed of response of any sensor dependent upon the smart sensor. Smart sensors allow multisensor interaction and changes in sensor configuration for more thorough measurement or sensing capability. Smart sensors will provide information directly to the user instead of only raw data.

CONCEPTUAL DIAGRAM OF SMART SENSOR FOR RENDEZVOUS AND PROXIMITY OPERATIONS



10-20

CONCEPTUAL DIAGRAM OF SMART SENSOR FOR RENDEZVOUS AND PROXIMITY OPERATIONS

The accompanying figure shows a conceptual diagram of the manner in which a smart sensor would operate for rendezvous and proximity operations. Here the source generates a physical measureable which is transmitted (the stimulus). The stimulus interacts with the sensor portion of the smart sensor to produce measured quantities. The values of the measured quantities are processed by the processor portion of the smart sensor to produce information. The information is transmitted to the user/system controller. Based on this information, the system controller produces changes in the system of interest. As the system changes, changes are produced in the source of the stimulus. This cycle is reproduced until a desired action occurs, that is, a vehicle is docked or a remote manipulator grasps an object or vehicle.

10-21

EMERGING TECHNOLOGIES FOR SMART SENSOR DEVELOPMENT

- Sensor-oriented technologies:
  - Large silicon-based CCD arrays for visible and near infrared imaging
  - III-V and II-VI infrared CTD's
  - High-power, semiconductor diode lasers
  - Tunable spectral filters
- Processor-oriented technologies:
  - VLSIC/VHSIC
  - Gallium arsenide IC's
  - Fiber optics/integrated optics
  - Semiconductor diode lasers

EMERGING TECHNOLOGIES FOR SMART SENSOR DEVELOPMENT

The emerging technologies which will significantly facilitate the development of smart sensors for future spacecraft applications are listed in the accompanying figure. They are grouped under the subheadings of sensor-oriented technologies and processor-oriented technologies. Under sensor-oriented technologies, the first technology listed is large silicon-based charge coupled device arrays for visible and near infrared imaging. The next is III-V and II-VI infrared charge transfer devices. The last two are high-power, semiconductor diode lasers and tunable spectral filters. Under processor-oriented technologies, very large scale integrated circuits (VLSIC) and very high speed integrated circuits (VHSIC) are listed first. These technologies are advancing rapidly and will be the basis for the development of microprocessors/microcomputers with increased computational capability. The next technology is gallium arsenide integrated circuits which yield much higher speed circuitry than silicon. Fiber optics and integrated optics will be used for high speed data transfer between smart sensors and to the onboard data management system. Semiconductor diode lasers will be used as coherent radiation sources to produce radiation for propogation in fiber optics.

CONCLUDING REMARKS

- With a primary stimulus from the electronics industry, smart sensors (or, integrated sensors) will continue to evolve.
- Smart sensors will have a definite impact on rendezvous and proximity operations.
- Smart sensors will permit more effective performance of systems used in rendezvous and proximity operations.
- Improved system performance will ultimately be reflected in lower operations cost.

CONCLUDING REMARKS

Concluding remarks are listed in the accompanying figure. Smart sensors or integrated sensors will continue to evolve with the primary stimulus being produced by the electronics industry. Smart sensors will have a definite impact on rendezvous and proximity operations, especially as automation and robotics come more into play. They will permit more effective performance of systems employed in rendezvous and proximity operations. Finally, this improved system performance will be reflected ultimately in lower operations cost.

10-25

Title	Division/Office	
OPTICAL SHUTTLE SENSOR AND TELEVISION PROXIMITY SYSTEM OVERVIEW	TRACKING & COMMUNICATIONS DIVISION	
	Presenter: OLIN GRAHAM	Date: JANUARY 1985

- SHUTTLE CLOSED CIRCUIT TELEVISION SENSOR
- SHUTTLE EVA SOLID STATE CCD SENSOR
- SHUTTLE EVA COLOR TELEVISION SENSOR
- OTHER SENSORS EVALUATED FOR PROXIMITY OPERATIONS
- TELEVISION PROXIMITY SYSTEM MEASUREMENT REQUIREMENTS
- ADDITIONAL TELEVISION DESIGN FEATURES FOR ACHIEVING A PROXIMITY SYSTEM
- SHUTTLE EXPERIENCE
- MAJOR UNRESOLVED TELEVISION PROXIMITY DESIGN AREAS

10-26

Title	Division/Office	
SHUTTLE CLOSED CIRCUIT TELEVISION SENSOR	TRACKING & COMMUNICATIONS DIVISION	
	Presenter: OLIN GRAHAM	Date: JANUARY 1985

- 16 MM SILICON INTENSIFIED VIDICON
- SYSTEM RESOLUTION $\simeq$ 400 TV LINES/PICTURE HEIGHT
- LOW LIGHT LEVEL $\simeq 10^{-3}$ FOOT CANDLES FACEPLATE ILLUMINATION
- INTRA-SCENE DYNAMIC RANGE $<$ 100/1
- INTER-SCENE DYNAMIC RANGE $\simeq 0.5 \times 10^{6}$
- FIELD SEQUENTIAL COLOR AND MONOCHROME
- S-20 PHOTO CATHODE
- SENSOR OVERLOAD -- MARGINAL FOR PROXIMITY OPERATIONS CONTROL

Title	Division/Office	
SHUTTLE EVA SOLID STATE CCD SENSOR	TRACKING & COMMUNICATIONS DIVISION	
	Presenter OLIN GRAHAM	Date JANUARY 1985

- LINE TRANSFER
- 380 x 488 ELEMENTS
- LOW LIGHT LEVEL $\simeq$ 10^{-1} FOOT CANDLES FACEPLATE ILLUMINATION
- INTRA-SCENE DYNAMIC RANGE < 100/1
- VISIBLE RESPONSE
- SENSOR OVERLOAD -- MARGINAL FOR PROXIMITY OPERATIONS WITHOUT BLOOMING CONTROL

10-28

Title	Division/Office	
SHUTTLE EVA COLOR TELEVISION SENSOR	TRACKING & COMMUNICATIONS DIVISION	
	Presenter OLIN GRAHAM	Date JANUARY 1985

- MOS TECHNOLOGY
- SINGLE CHIP COLOR CONFIGURATION
- INTRA-SCENE DYNAMIC RANGE < 100/1
- VISIBLE RESPONSE
- SENSOR OVERLOAD -- FAIR FOR PROXIMITY OPERATIONS CONTROL
- SYSTEM RESOLUTION 250 TV LINES/PICTURE HEIGHT

10-29

Title	Division/Office	
OTHER SENSORS EVALUATED FOR PROXIMITY OPERATIONS	TRACKING & COMMUNICATIONS DIVISION	
	Presenter OLIN GRAHAM	Date JANUARY 1985

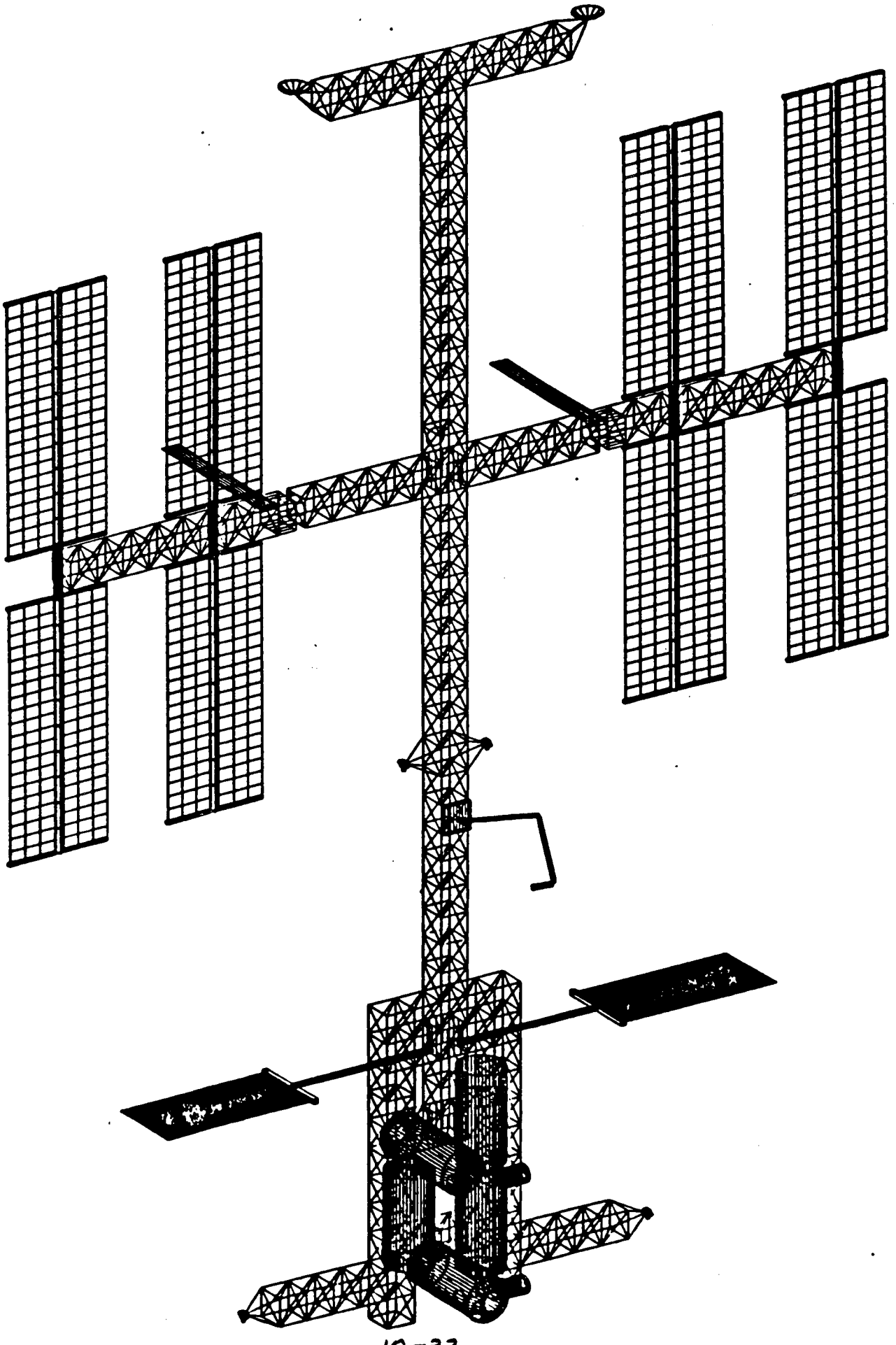
- CHARGE INJECTION DEVICE
  - 388 x 244 ELEMENTS
  - INTEGRATING -- VARIABLE FRAME RATE
  - INTENSIFIED

- CCD FRAME TRANSFER
  - 403 x 488
  - MONOCHROME AND COLOR CONFIGURATION

10-30

SPACE STATION

(COMPUTER ARTIST'S CONCEPT)



10-32

- OBJECT RANGE
  (1 METER TO 200 METERS)

- OBJECT RATE
  (0 TO 3 METERS/SECOND)

- POSITION
  (± 1 METER IN A 200-METER DIAMETER SPHERE)

- ATTITUDE
  (± 5° ROLL, PITCH, YAW)

10-33

Title	Division/Office	
ADDITIONAL TELEVISION DESIGN FEATURES FOR ACHIEVING A PROXIMITY SYSTEM	TRACKING & COMMUNICATIONS DIVISION	
	Presenter: OLIN GRAHAM	Date: JANUARY 1985

- PROGRAMMABLE AND AUTOMATED
  - OBJECT RECOGNITION
  - IMAGE TRACKING
  - ZOOM

- AUTOMATED
  - FOCUS
  - IRIS
  - BLOOMING CONTROL

10-34

Title	Division/Office	
SHUTTLE EXPERIENCE	TRACKING & COMMUNICATIONS DIVISION	
	Presenter OLIN GRAHAM	Date JANUARY 1985

- LASER RANGING DEVICE FLOWN WITH SHUTTLE CAMERA
  - MEASURED RANGE TO EVA CREWMAN AT 300 FEET
  - RANGE INTEGRATED TO DETERMINE RANGE RATE

- SHUTTLE CAMERA SYSTEM PROVIDES PAN/TILT ANGLE MEASUREMENTS OF 0.2 DEGREES PER STEP (POSITION CALCULATABLE FROM PAN/TILT COORDINATES)

- DESIGN GROUND TESTED FOR AUTO FOCUS AND AUTO ZOOM AS FUNCTION OF RANGE

10-35

Title	Division/Office	
PRESENT LABORATORY PROXIMITY ACTIVITIES	TRACKING & COMMUNICATIONS DIVISION	
	Presenter: OLIN GRAHAM	Date: JANUARY 1985

- TELEVISION SPACE STATION TEST BED
  - DATA AND COMMAND CONTROL TECHNIQUES
  - VIDEO DATA COMPRESSION/REDUCTION TECHNIQUES
    - SCAN AND FRAME RATE (FORMAT) IMPROVEMENTS
  - AUTO TRACKING TECHNIQUES
    - AMPLITUDE
    - SPATIAL
    - SPECTRAL
  - ATTITUDE DETERMINATION TECHNIQUES
    - OPTICAL MATCHING
    - MOMENT INVARIANT STUDY

Title	Division/Office	
MAJOR UNRESOLVED TELEVISION PROXIMITY MEASUREMENT AND DESIGN AREAS	TRACKING & COMMUNICATIONS DIVISION	
	Presenter OLIN GRAHAM	Date JANUARY 1985

- MEASUREMENT OF OBJECT ATTITUDE USING A SINGLE SENSOR

- DEFINITION/DESIGN OF ADEQUATE RECOGNITION ALGORITHMS
- AUTOMATED IMAGE TRACKING UNDER EXTREMELY WIDE DYNAMIC LIGHT RANGE
- AUTOMATED IMAGE TRACKING IN THE PRESENCE OF EXTREME BACKGROUND CLUTTER

10-37 / 10-34

INTENSIFIED CCD CAMERAS FOR LOW LIGHT LEVEL APPLICATIONS

KENNETH A. HOAGLAND

FAIRCHILD WESTON SYSTEMS INC.
SYOSSET, NEW YORK 11791

FAIRCHILD WESTON
Schlumberger

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10-39

INTENSIFIED CCD CAMERAS FOR LOW LIGHT LEVEL APPLICATIONS

K.A. HOAGLAND

Fairchild Weston Systems, Inc.

Image intensifiers originally developed for night vision equipment can be combined with CCD and other solid state image detectors to modify and extend the performance range of optical sensor systems designed for space applications. Features and characteristics of intensified CCD cameras based on second generation (GEN II) microchannel plate intensifiers are described, including a discussion of performance observations with prototype low-light level TV cameras. Other topics include the use of image intensifiers as electronic shutters, and the feasibility for operation in selected spectral regions ranging from X-ray to the near IR. The presentation concludes with a discussion of a recommended dual-channel system concept using an optical beam-splitter or path-switcher for simultaneous or independent operation of intensified and non-intensified image detector channels.

INTENSIFIED CCD CAMERAS FOR LOW LIGHT LEVEL APPLICATIONS

- IMAGE INTENSIFIER PRINCIPLES
- GEN I, II AND III DEVICES
- FIBER OPTIC COUPLING
- HIGH VOLTAGE POWER SUPPLIES/PULSE GATED OPERATION
- LOW LIGHT LEVEL PERFORMANCE TRADE-OFFS
- DAY/NIGHT CAMERA CONCEPT

Although Image Intensifiers were originally developed for use in direct-view night vision equipment, these devices, with relatively simple modifications, can be used to extend the useful illumination range of CCD and other solid state imager (SSI) systems by several decades.

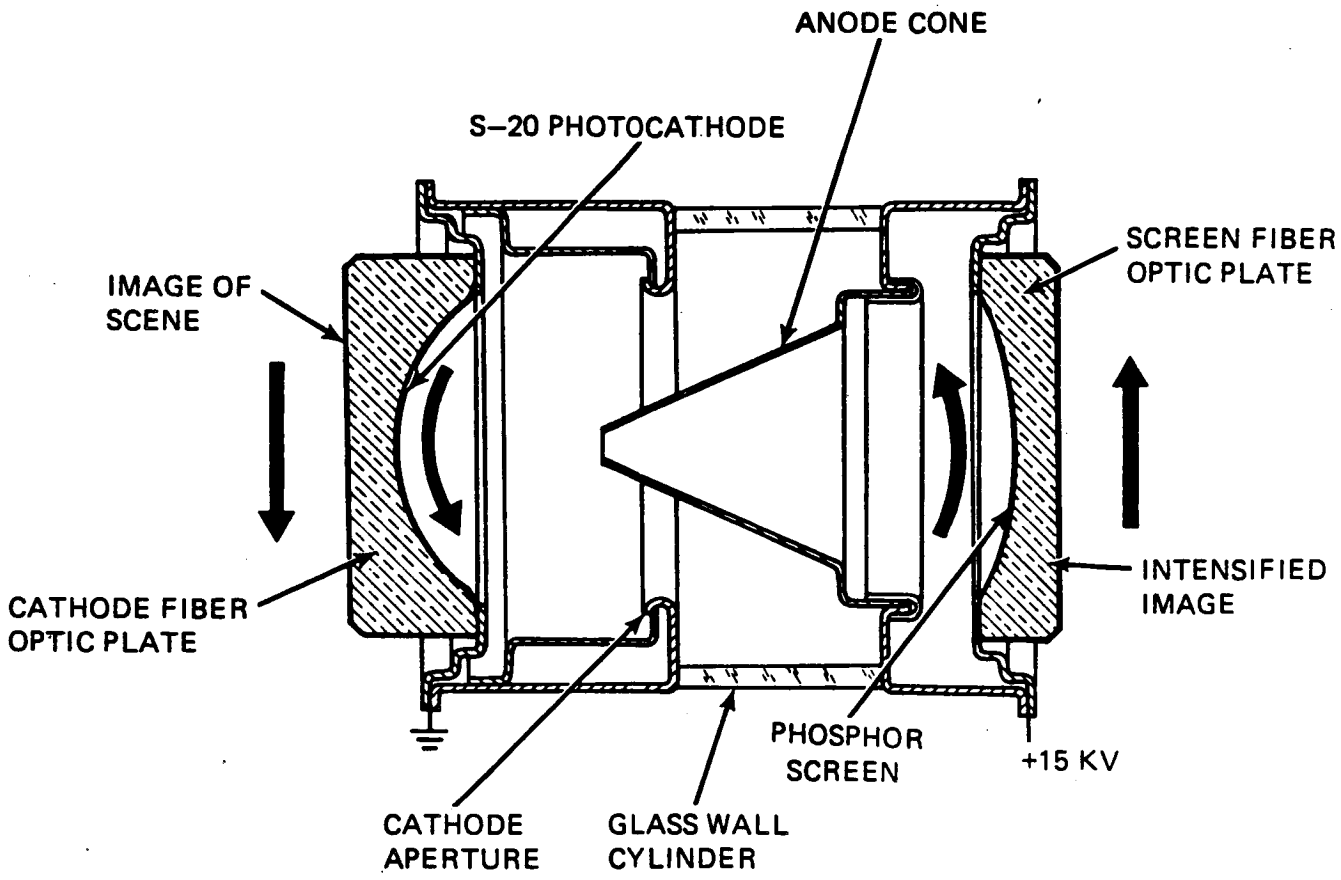
Features and operating principles for the direct-view application also apply for Intensifier SSI systems, with the exception of the requirement for inversion of the intensifier output image.

IMAGE INTENSIFIER PRINCIPLES

- OBJECTIVE LENS PROVIDES INVERTED SCENE IMAGE TO PHOTOCATHODE (PC)
- PHOTON TO ELECTRON CONVERSION AT PHOTOCATHODE IN VACUUM SPACE
- AMPLIFICATION BY ELECTRON ENERGY INCREASE OR ELECTRON MULTIPLICATION
- IMAGE INVERSION — OPTICAL, ELECTRO-OPTICAL, OR FIBER OPTIC TWISTER
- PHOSPHOR OUTPUT SCREEN FOR ELECTRON TO PHOTON CONVERSION

First generation (GEN I) image intensifiers achieve light amplification by a photon-electron-photon conversion process supplemented by acceleration-induced electron energy gain. Luminous gains of 100 are typical with tungsten light input and 15 KV acceleration. The electrostatic focus lens, (which causes image inversion), is fixed in strength by electrode dimensions and spacings. Focus is independent of applied voltage for relatively large supply voltage variations.

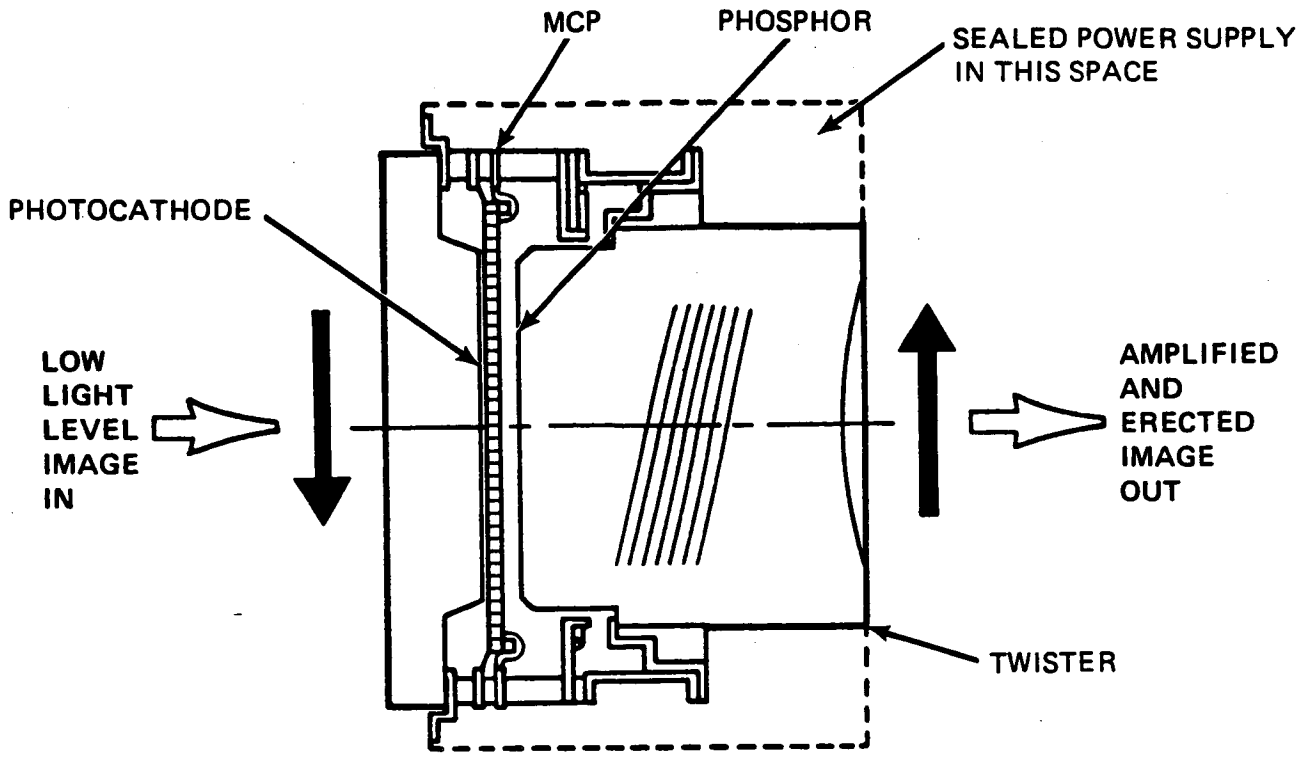
Resolution for GEN I tubes is high, typically exceeding 60 lp/mm at the center. The curved fiber optics provide off-axis focus and pattern-distortion correction.



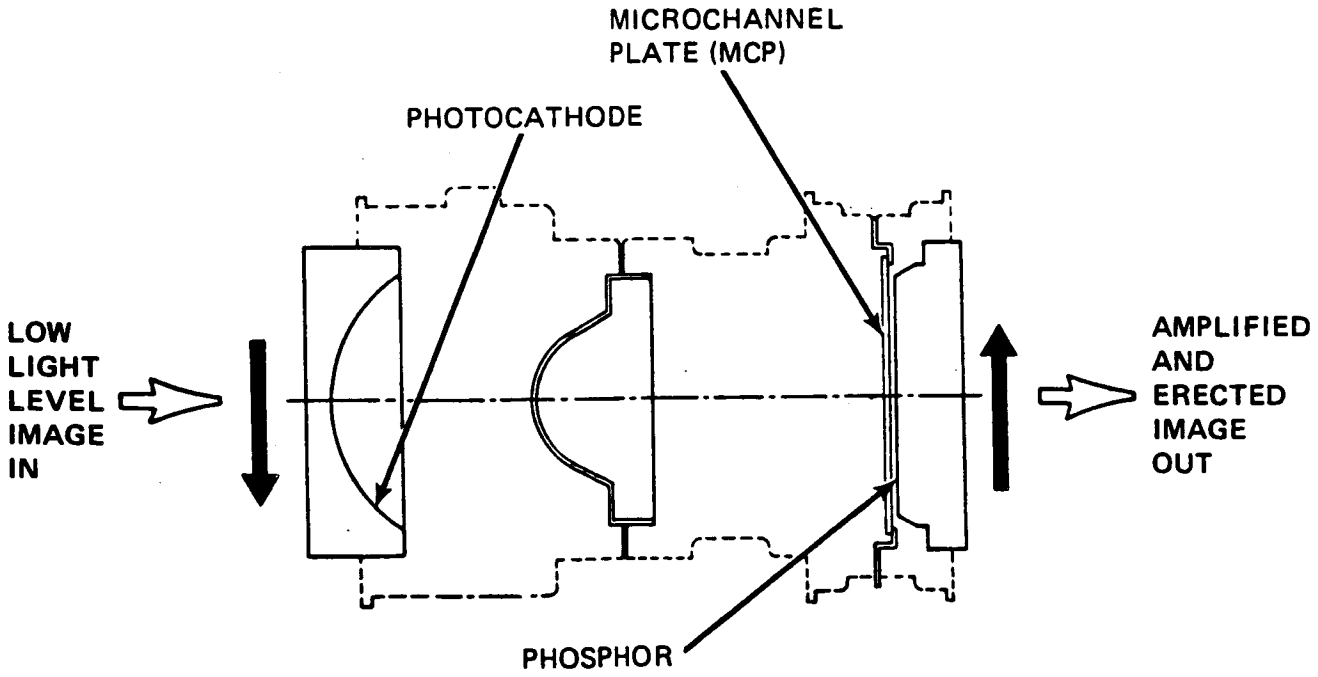
GEN 1 INTENSIFIED TUBE

Second generation (GEN II) intensifiers use electron multiplication to increase current flow to the output screen. Individual electron multiplier channels are created by etching-out the core glass from a thin wafer made from material similar to a fiber optic faceplate. After processing, the microchannel plate (MCP) wafer provides high current gain (typically $10^3/1$ to $10^4/1$) with potentials of less than 900 volts applied to the surface electrodes.

Luminous gains can be $\geqslant$ 30,000 for the Inverter-MCP design, with a limiting resolution near 30 lp/mm. The proximity-focused Wafer-MCP type typically exhibits lower gain (10,000 to 20,000 max.), with 25 to 30 lp/mm resolution. Wafer-MCP devices are preferred however, for applications requiring small size, low pattern distortion or electronic shuttering.



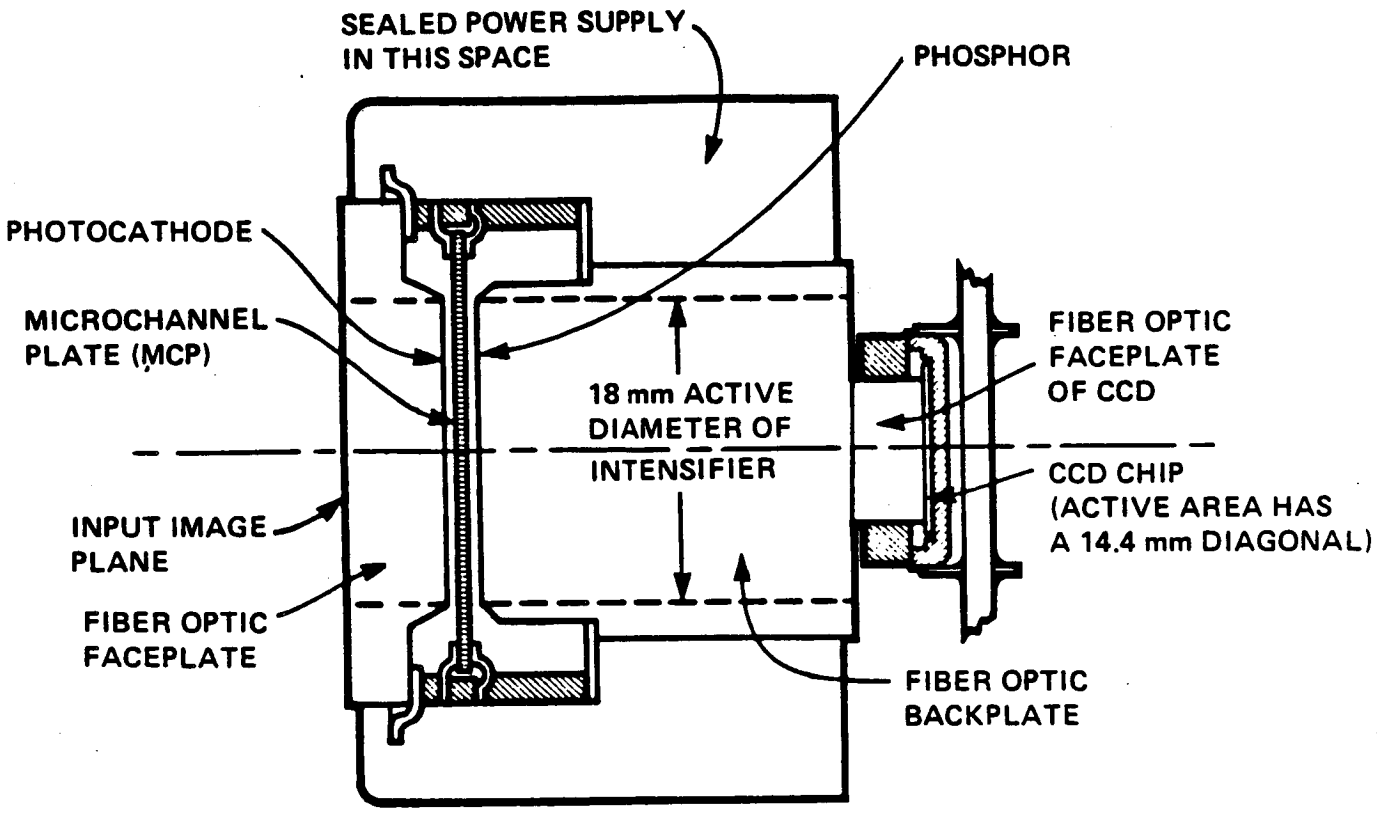
GEN II WAFER TUBE



GEN II INVERTER TUBE

A sensor assembly consisting of an 18mm wafer MCP tube, coupled by unity magnification fiber optics to a CCD array can be used for constructing a relatively simple and compact low light level camera.

The tube and power supply components are identical to components produced for direct-view night vision applications with the exception of the fiber optic backplate, which is modified to interface with the CCD fiber optics.



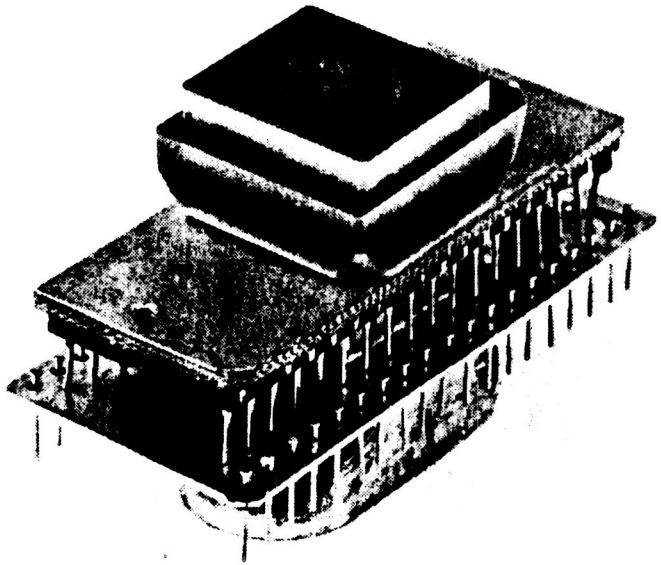
INTENSIFIER/CCD SENSOR DETAILS

Fiber-optic CCD Module Assemblies have been constructed with thermoelectric devices in sealed enclosures to provide CCD temperature control. The viewgraph illustrates an assembly with a single-stage cooler and a 25/18 fiber optic minifier.

Similiar assemblies have been successfully tested in space experiments. Five assemblies, each containing a three stage TE cooler, a 190x244 element CCD and a 1.3/1 fiber optic minifier, were used with GEN II Image Intensifiers for spectroscopic imaging of the thermosphere from the Space Shuttle.

FAIRCHILD WESTON SYSTEMS INC.

Fairchild Systems



FIBER OPTIC-CCD MODULE ASSEMBLY, WITHOUT CASE ENCLOSURE

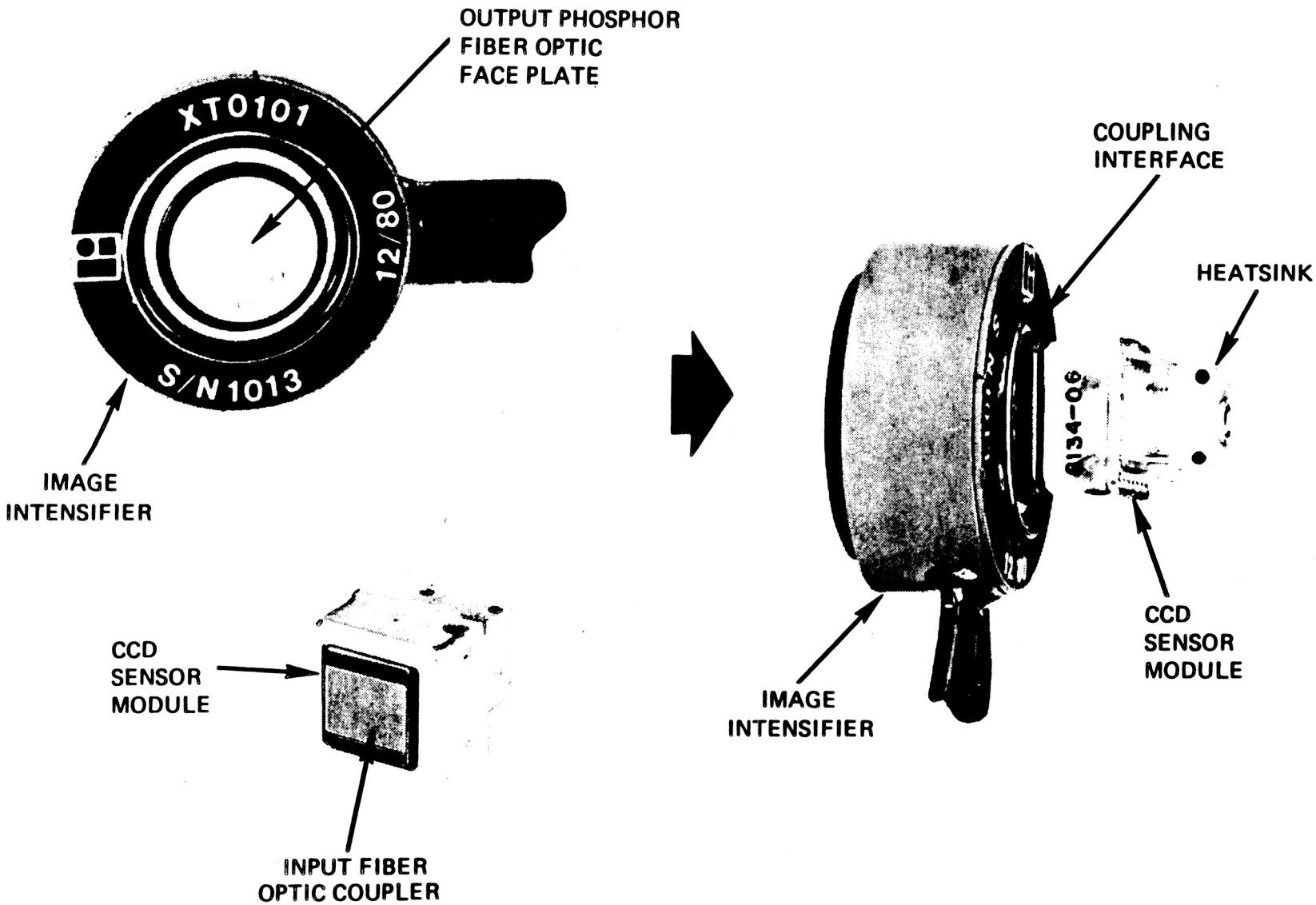
77558
84-280

FAIRCHILD WESTON
Schlumberger

12
10-51

Image Intensifier/CCD Sensor Modules have been developed for aerospace applications requiring exposure to relatively severe shock, acceleration and thermal environments. The view-graph illustrates components of a sensor package designed for such applications.

In this case the intensifier is equipped with flexible leads for connection to a remote high voltage supply which operates the tube in an electronic shuttering or "gated" mode.

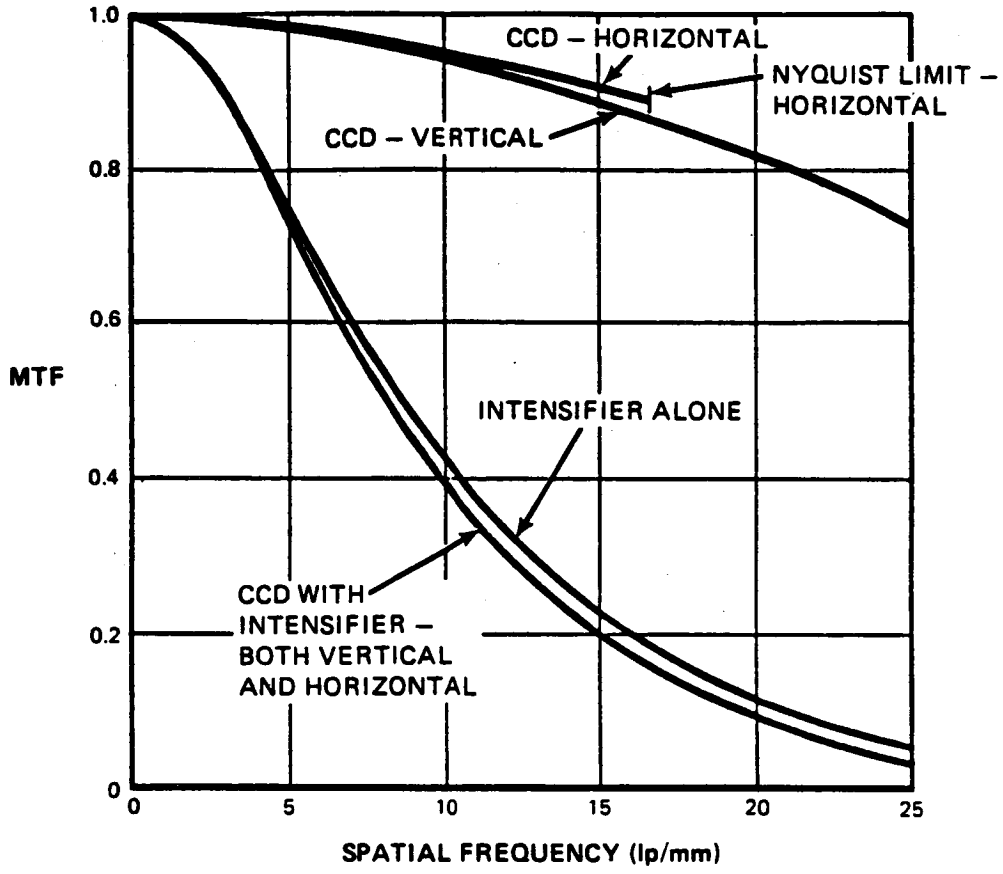


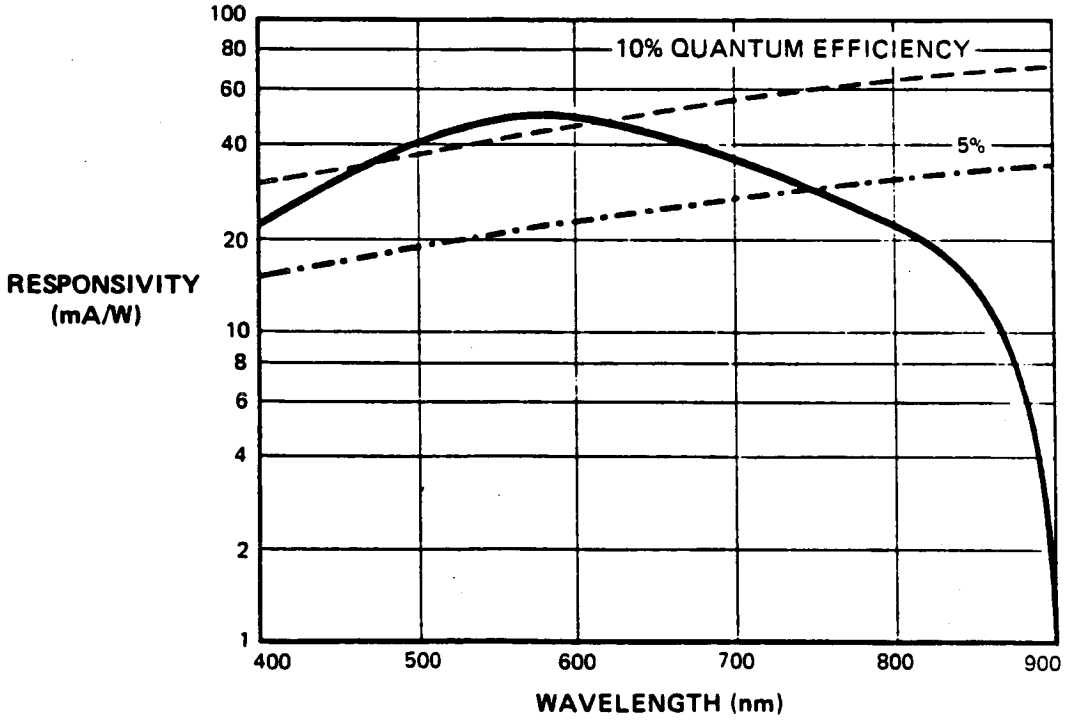
CCD COUPLED TO IMAGE INTENSIFIER

82-074
820032

The spacing between channels of the MCP structure, and proximity-focusing effects, are the principal factors limiting useful MTF to spatial frequencies less than 30 lp/mm. For the combined Intensifier and CCD the MTF values of the combination are typically close to the values observed for the Intensifier alone.

Photocathode responsivity for the S20 surface peaks in the visible spectrum, with useful response extending from the near UV to near IR regions. UV response can be extended to below 200 nm with photocathodes deposited on a fused silica faceplate.





PC RESPONSIVITY AND MTF CHARACTERISTICS

Although camera systems can be devised to operate with a single Intensifier/SSI Sensor over the entire natural illumination range (starlight to full sun) system performance can be improved with separate sensors for high and low light level operation.

The image intensifier (as with most components added in the optical path) will reduce image contrast and system MTF. Also, the ALC subsystem will be required to provide light attenuation factors $\geq 10^{-8}$ to avoid illumination overload. These and other considerations favor the concept of separate image sensor channels for cameras designed to operate over the starlight-to-sunlight illumination range.

INTENSIFIER/SSI APPLICATION CONSIDERATIONS

ADVANTAGES

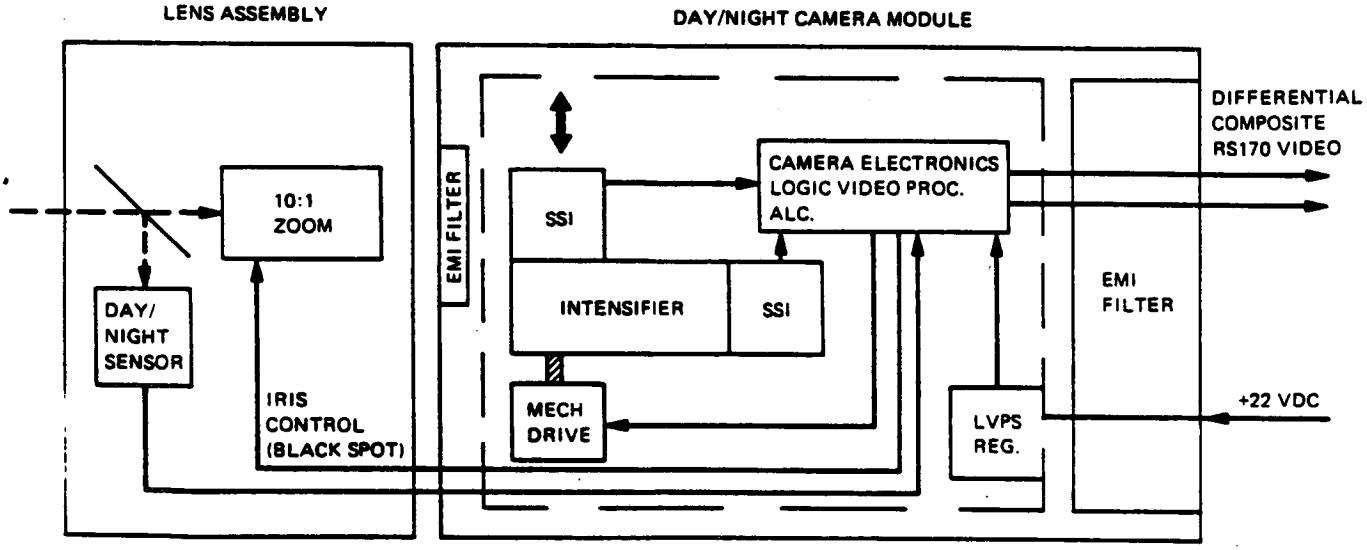
- HIGH ILLUMINATION SENSITIVITY
  - SYSTEM RESOLUTION AT LOW LIGHT LEVEL APPROACHES NOISE-IN-SIGNAL LIMIT
- HIGH IN-SCENE AND INTRA-SCENE DYNAMIC RANGE
  - MCP SATURATES WITH LOCAL OVERLOADS
  - ALC/AGC RANGE CAN EXCEED $10^8/1$
- EXCELLENT ELECTRONIC SHUTTER CHARACTERISTICS

DISADVANTAGES

- MTF/RESOLUTION LOSS
- INTENSIFIER MUST BE PROTECTED FROM ILLUMINATION OVERLOADS
- HIGH-VOLTAGE POWER SUPPLIES NEEDED

The small size, weight, and power requirements typical for solid state imagers and GEN II image intensifiers enable a variety of design approaches for dual-channel cameras. The block diagram illustrates an automatic mechanical changeover of day and night sensor channels.

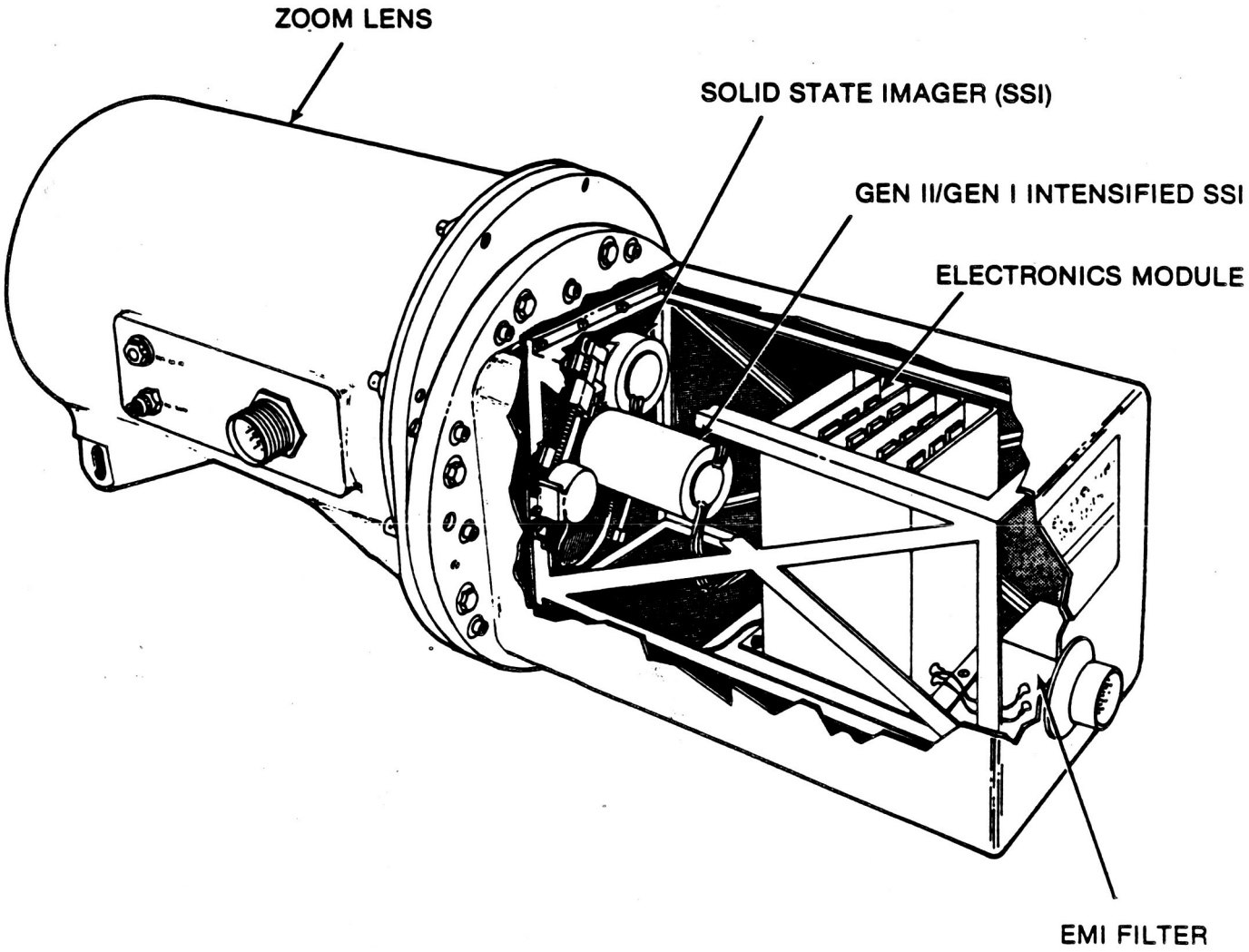
Other candidate dual channel techniques include systems based on beam-splitter prisms and optical channel switches using movable prisms or mirror surfaces.



BLOCK DIAGRAM
DAY/NIGHT SOLID STATE IMAGER (SSI) CAMERA

The viewgraph illustrates details of a prototype Day/Night Solid State Camera using an Intensifier/SSI night channel sensor. The Intensifier in this case consists of cascaded GEN II and GEN I stages providing luminous gain in excess of 10^5.

The intensified and non-intensified SSI channels are mounted on a common platform arranged to enable indexing of either sensor channel to the output image location of the zoom optics.



DAY/NIGHT SOLID STATE CAMERA

"ADVANCED VISIBLE AND INFRARED IMAGE SENSORS"

by

Walter F. Kosonocky
RCA Laboratories
Princeton, NJ 08540

10-22

RCA

Outline

- VISIBLE (0.4 to 0.7 μm) 403 x 512 FT-CCD IMAGER
- VIS/NIR (0.4 to 0.9 μm) 4 x 1024 MULTI-SPECTRAL LINEAR IMAGER (BUTTABLE)
- SWIR (1 to 3 μm) 2 x 512 Pd_2Si IR-CCD MULTI-SPECTRAL LINEAR IMAGER (BUTTABLE)
- MWIR (3 to 5 μm) 160 x 244 PtSi IR-CCD STARTING IMAGER
- VIDEO TAPE DEMONSTRATION OF THERMAL IMAGING WITH 160 x 244 PtSi IR-CCD TV CAMERA

10-23

For B/W and color TV applications in the 400 to 700 nm spectral range RCA developed a 403 x 512 (V)-element frame-transfer CCD image sensor with 16 (H) x 20 (V)-μm^2 pixels and 316 (H) x 416 (V)-mil^2 chip size. This imager is constructed with three-phase triple-level-polysilicon buried channel register, "Buried" overflow drains with implanted barriers, and the illuminated register operated with 2:1 vertical interlace. This is a thinned (to about 10 μm) back-illuminated imager that allow almost 100% utilization of the incident light, has quantum efficiency exceeding 60% over the entire visible spectrum, and for operation with a high-pass-filter sample-and-hold circuit has a readout noise floor of 60 rms electrons.

49-01

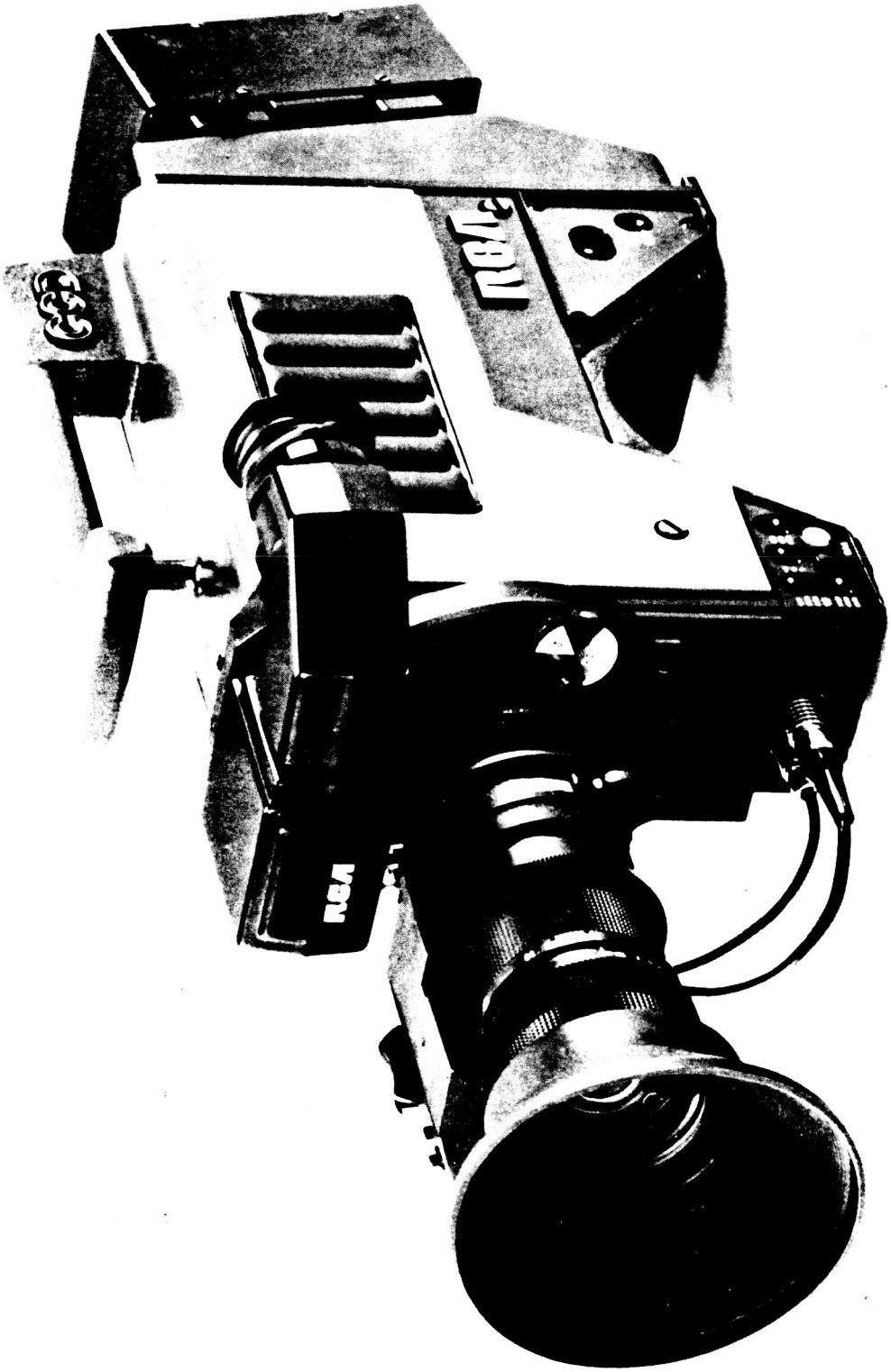
RCA Unique Features of 403 (H) x 512 (V) FT-CCD Imager

- CONSTRUCTION
  - THINNED (TO 10 to 25 μm) FOR BACK ILLUMINATION
  - LAMINATED ON GLASS SUBSTRATE
  - "BURIED" BLOOMING (OVER FLOW) DRAINS
- PERFORMANCE
  - HIGH QUANTUM EFFICIENCY
    - 60% BLUE
    - 70% GREEN AND RED
  - NO BLOOMING
    - FOR 10,000X OVER LOAD
  - LOW AND UNIFORM DARK CURRENT
    - 1000 ELECTRONS/PIXEL AT 32°C
  - LOW OUTPUT NOISE WITH HIGH-PASS SAMPLE-AND-HOLD
    - 55 RMS ELECTRONS/PIXEL

10-65

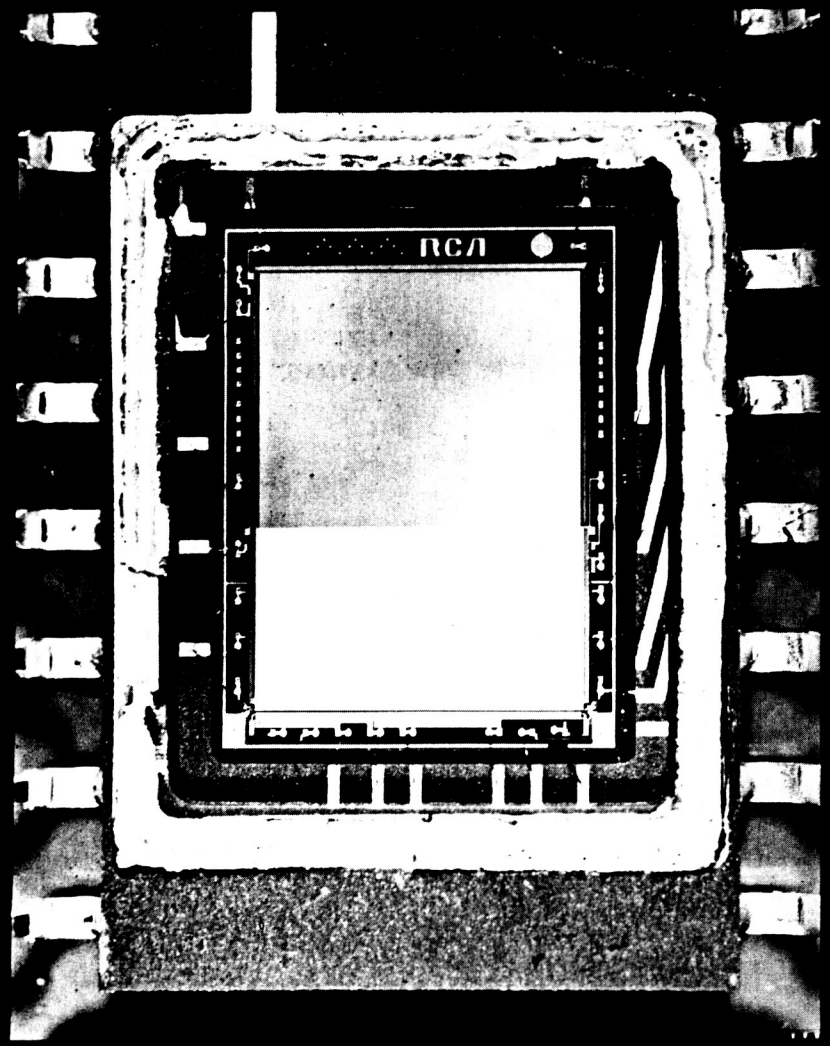
10-66

The 403 x 512 Frame Transfer Imager was developed at RCA for a 3-chip color portable broadcast camera shown on this photograph.


RCA

This photograph shows the 403 (H) x 512 (V) Frame Transfer Visible CCD Image Sensor bonded in a 16-pin ceramic package. The imager is illuminated through a window on the back side of the ceramic package.

RCA



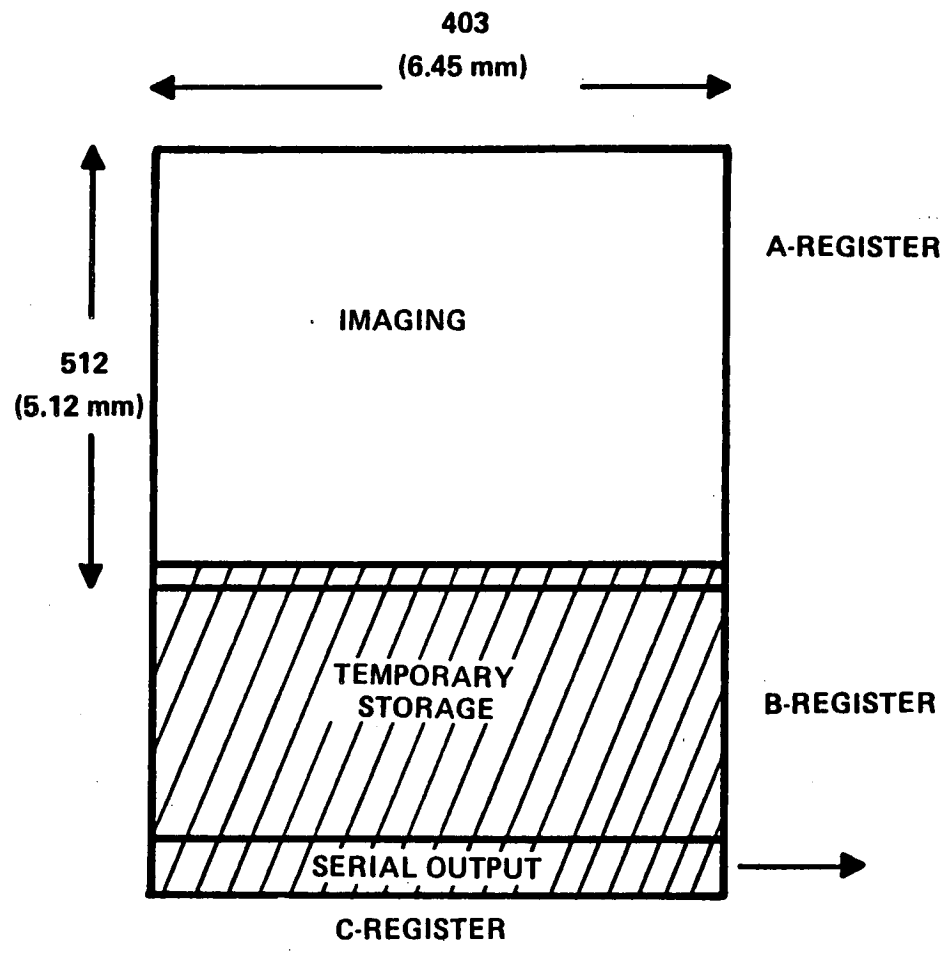
- 403(H) x 512(V) FRAME TRANSFER VISIBLE CCD IMAGER
- 16 x 20 μm PIXELS
- THINNED AND BACK SIDE ILLUMINATED

69-01

This figure illustrates the architecture of the visible imager which consists of a three-phase 403 (H) x 512 (V) pixel frame-transfer imager, with a chip area of 319 x 416 mil^2 and 16 (H) x 20 (V) micron pixels. The illuminated area of 6.45 (H)-mm x 5.12 (V)-mm is exposed to the optical signal. As will be illustrated in the following figures, this imager is constructed with three-phase triple-level-polysilicon buried channel register, "buried" overflow drains with implanted barriers, and an illuminated register operated with 2:1 vertical interlace.

RCA

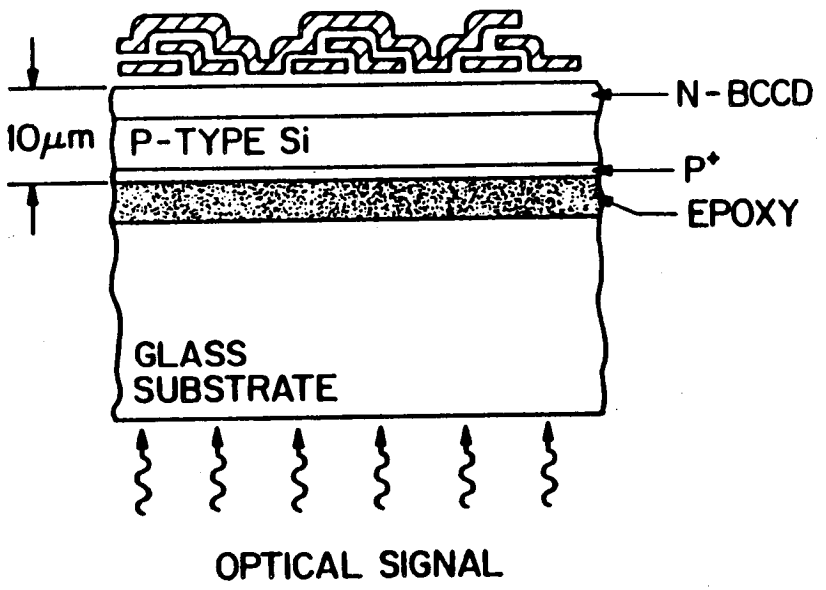
Architecture of RCA 403 x 512 Imager



10-72

This figure shows the cross-section of the vertical register along the CCD channel. The silicon substrate is thinned to 10 microns and laminated to a transparent glass substrate for mechanical support thus allowing almost 100% utilization of the incident light.

RCA Cross-Sectional View Along CCD Channel



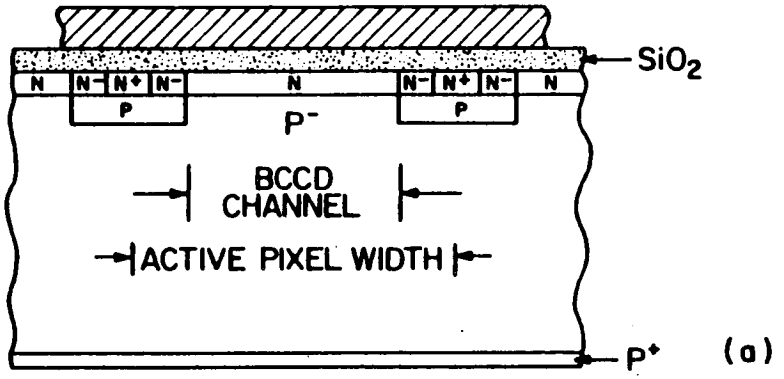
10-73

10-94

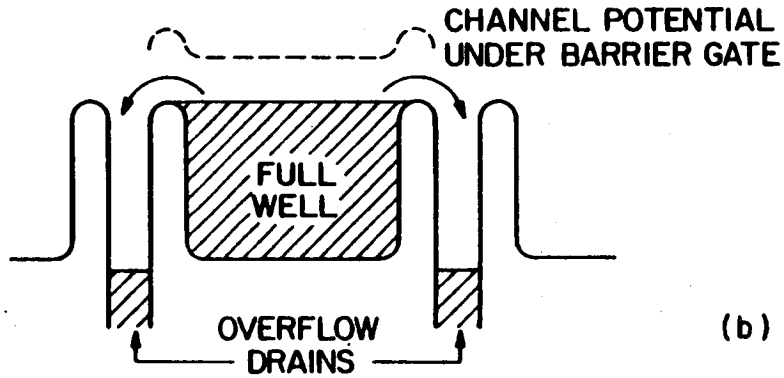
This figure shows the construction of "buried" overflow drains in which the undepleted p-type implant prevents any loss in quantum efficiency due to collection of photo-excited carriers from the bulk silicon by the antiblooming overflow drains. The overflow drains are capable of containing overloads of 10,000X. Transfer smear can be totally eliminated by the use of a mechanical shutter to block incident illumination from falling on the imaging register during the field transfer time.

RCA

Cross-Sectional View of Buried Overflow Drains and Potential Profile



(a)



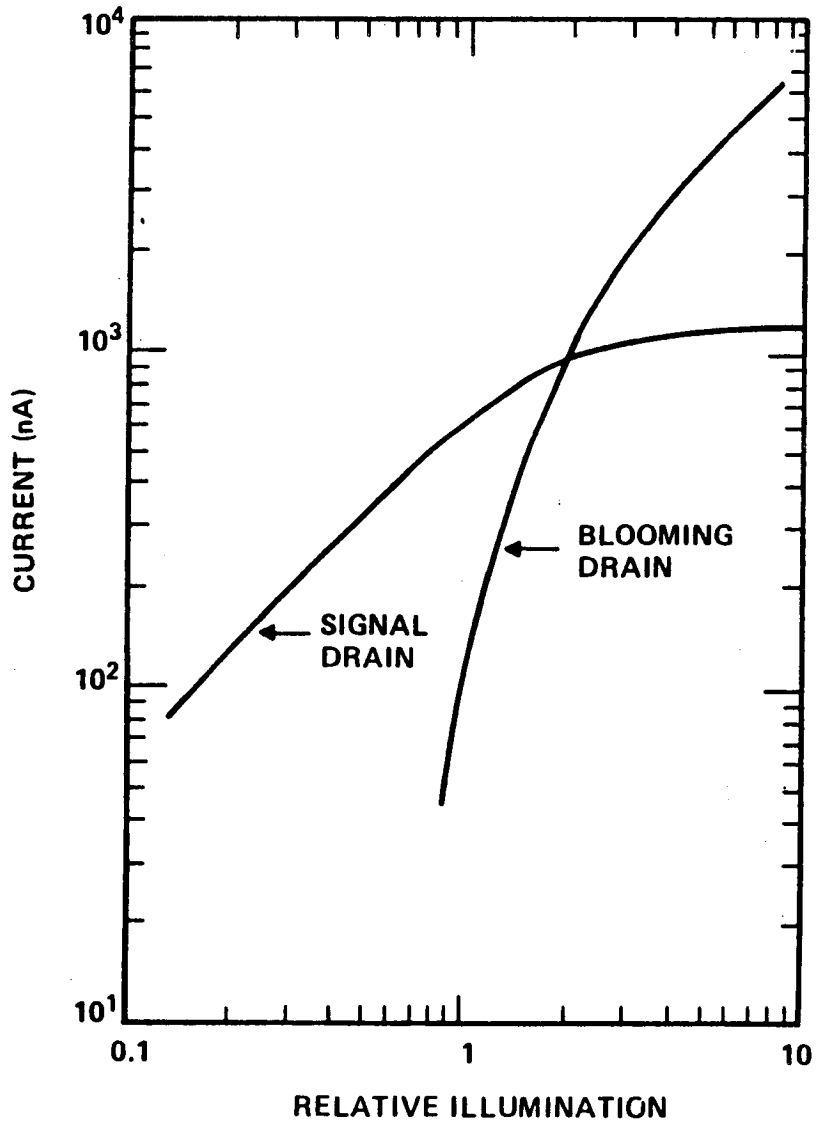
(b)

10-75

This figure shows the detected current (in nA) signal at the output drain of the serial CCD register and the measured current (in nA) at the blooming drains as function of optical input (relative illumination). For signal levels corresponding to less than a full-well, the signal detected by the blooming drains is neglegible.

RCA

Imager with Buried Blooming Drains



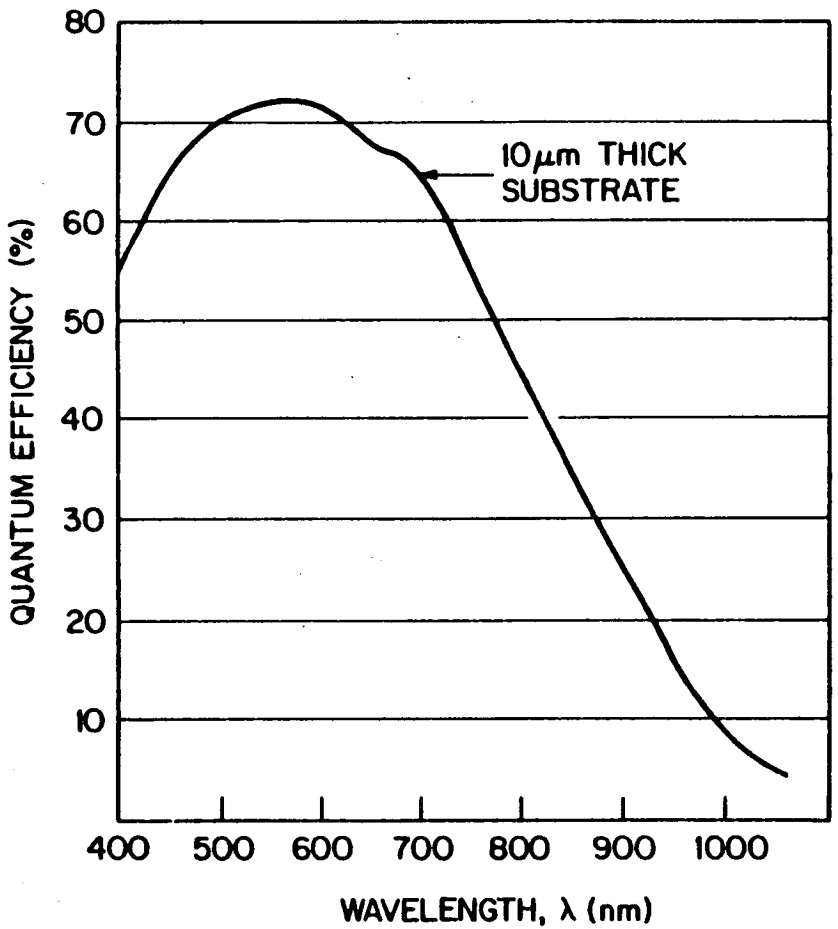
10-77

10-78

This figure demonstrates the quantum efficiency in excess of 60% over the entire visible spectrum (for wavelength from 400 to 700 nm).

RCA

Spectral Response of 403 x 512 Imager with Buried Blooming Drains



10-79

08-01

This figure plots the measured noise versus the device signal level. The readout noise floor of 55 rms electron was achieved by use of a high-pass-filter sample-and-hold circuit used to remove amplifier 1/f noise and floating diffusion reset noise.* A scene illumination of 80 lux gives a signal of 10^5 electrons/pixel with an F/1.4 lens and an IR blocking filter.

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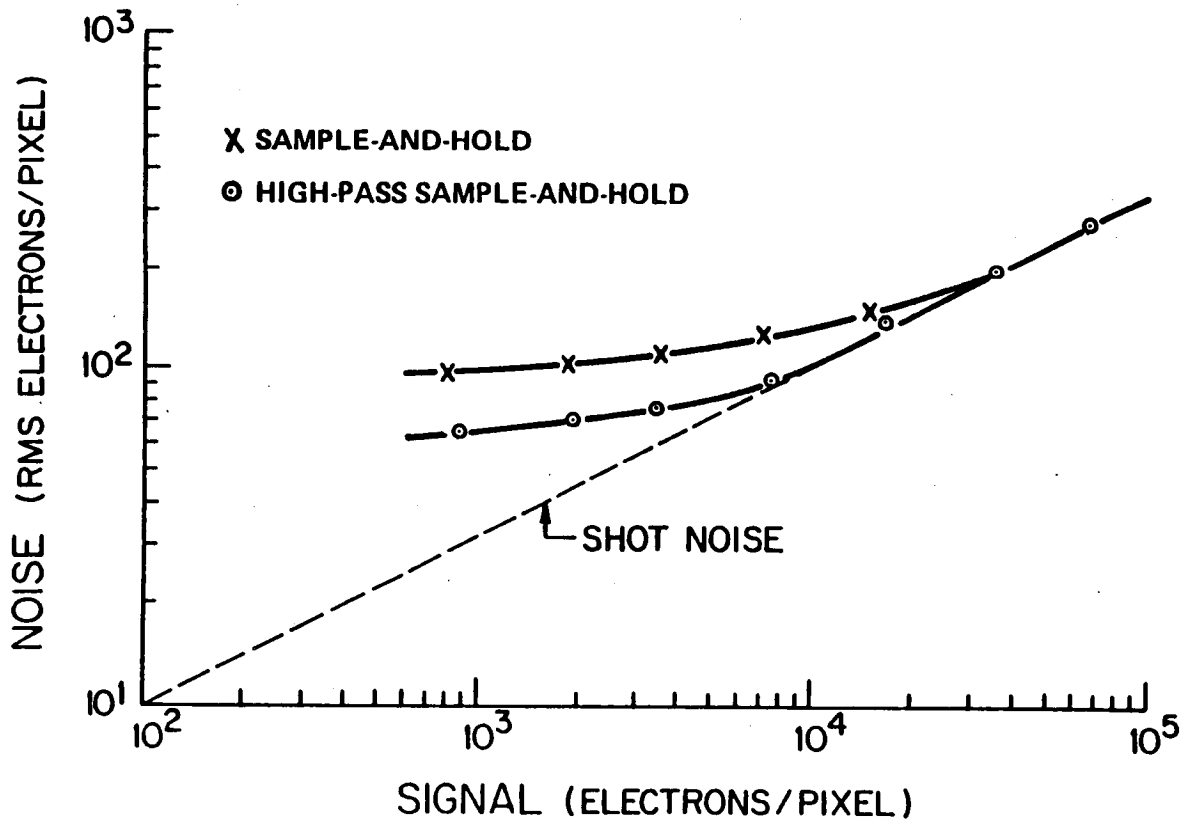
* The description of the high-pass-filter sample-and-hold circuit will be published by P. A. Levine in IEEE Transactions on Electron Devices for June, 1985.

Measured Noise for RCA 403 x 512 CCD Imager



18-01

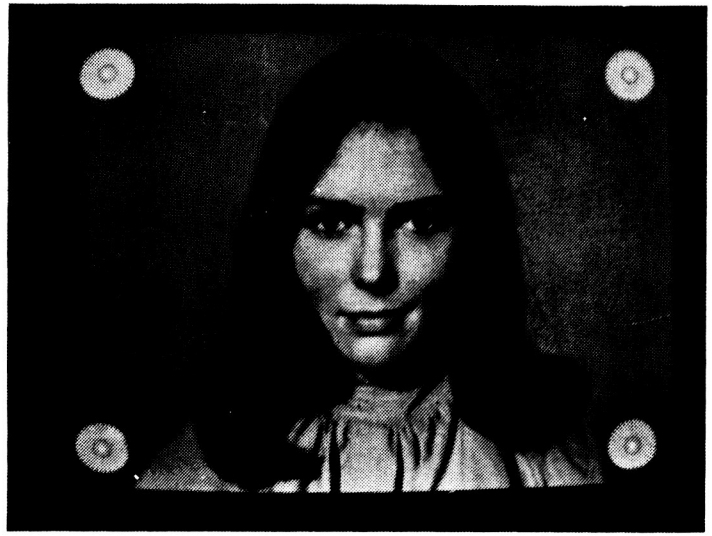
10-82

The exposure time of the photograph in this figure was 0.1 seconds corresponding to the response time of the eye. This figure illustrates that usable quality imaging (∿28 dB S/N) can be achieved with average scene illumination resulting in 1000 electrons/pixel which corresponds to only 1.0% of full well illumination. The device was operated at room temperature (with a chip temperature of 32°C) with dark current of about 1 na/cm^2 corresponding to 1000 electrons/pixel.

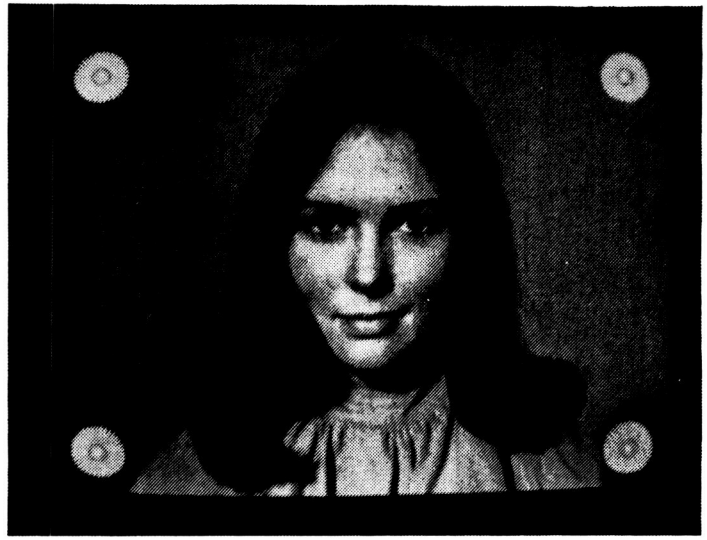
RCA

Low-Light Level Performance of 403 x 512 FT-CCD Imager

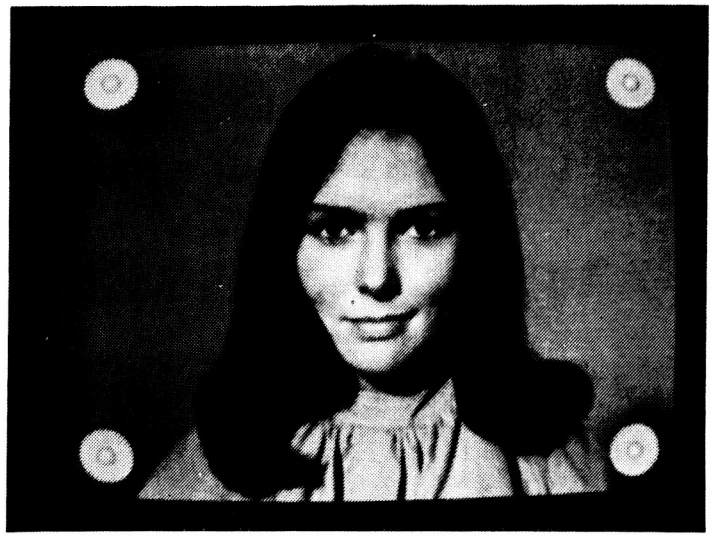
(FOR OPERATION AT 32°C WITH DARK CURRENT OF 1000 ELECTRONS/PIXEL)



100,000 ELECTRONS/PIXEL



300 ELECTRONS/PIXEL



1000 ELECTRONS/PIXEL

100 ELECTRONS/PIXEL

10-83

10-84

This table summarizes the characteristics of an RCA 403 (H) x 512 (V) Frame Transfer CCD Imager.

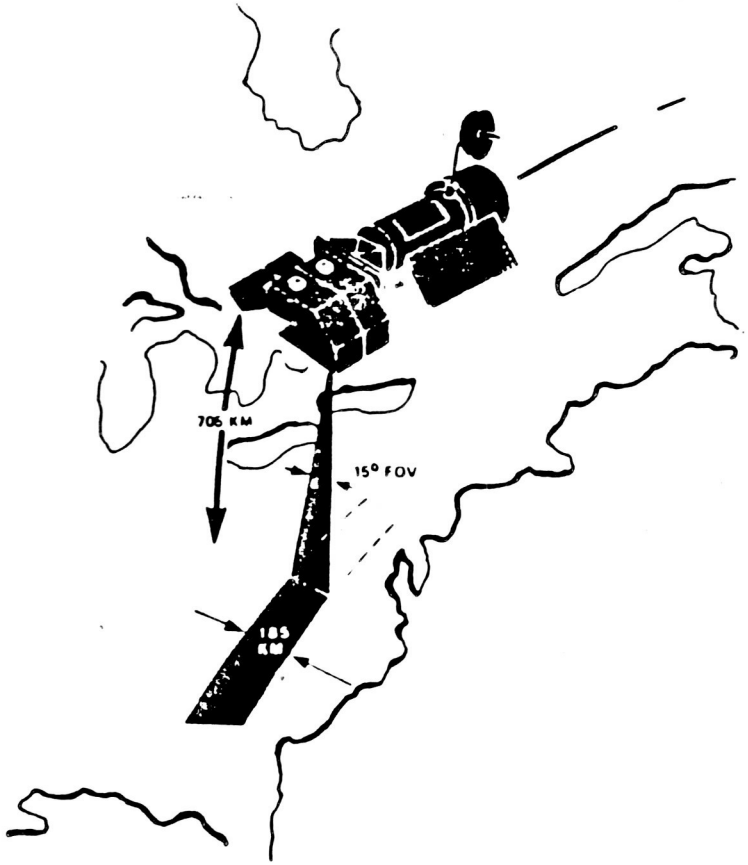
RCA 403 x 512 CCD Imager

IMAGER TYPE	F T, THINNED, BACK ILLUMINATED
NUMBER OF PIXEL	403 (H) x 512 (V)
IMAGE FORMAT	6.45 mm (H) x 4.88 mm (V)
FULL WELL	1×10^5 ELECTRONS
QUANTUM EFFICIENCY	70% (RED), 70% (GREEN), 60% (BLUE)
READOUT NOISE	55 ELECTRONS RMS
SENSITIVITY	1.5 LUX, F 1.4, 3000°K WITH IR CUT FILTER, S/N = 30dB
	0.3 LUX, F 1.4, 3000°K WITHOUT IR CUT FILTER' S/N = 30dB
HORIZONTAL RESOLUTION	300 TV LINES
VERTICAL RESOLUTION	350 TV LINES
OVERLOAD CAPABILITY	> 10,000 X

10-85

Two linear imager arrays, under development at RCA for NASA Multispectral Linear Array (MLA) instruments with a buttable construction for up to 12000 resoluton elements, are illustrated in the following three figures shown on pages 14, 15, and 16. Both of these arrays have been made with an edge-passivation structure that allows butting of adjacent arrays with a loss of only 2 pixels.

10-86



- NASA EARTH RESOURCES SATELLITE
- SURVEY 185 km SWATH WITH 15m/30m GROUND RESOLUTION
- 4 VISIBLE/NEAR IR AND 2 SWIR BANDS
- PASSIVE COOLING

VIS/NIR REQUIREMENT

- FOUR 12,000 ELEMENT LINEAR ARRAYS DIVIDED INTO 12 SUB-ARRAYS OF 4 X 1024 ELEMENTS EACH

SWIR REQUIREMENT

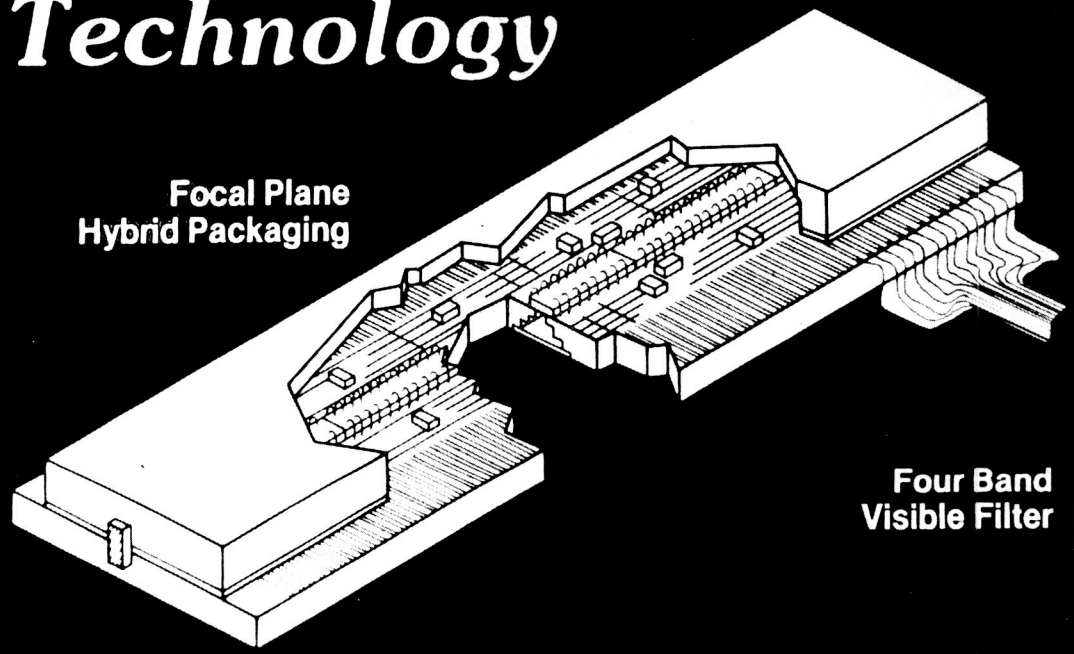
- TWO 6,000 ELEMENT LINEAR ARRAYS DIVIDED INTO 12 SUB-ARRAYS OF 2 X 512 ELEMENTS EACH

Multispectral Linear Array instrument concept.

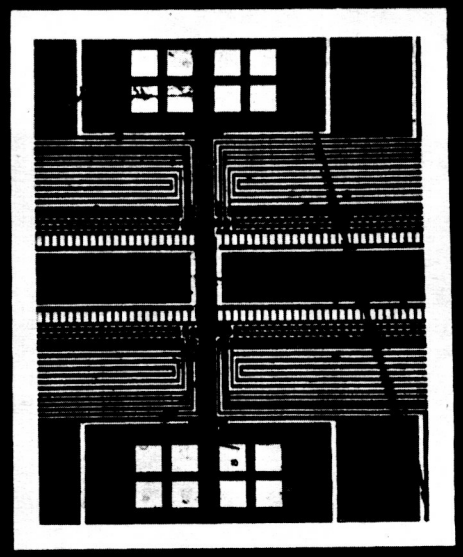
10-87

MLA Technology

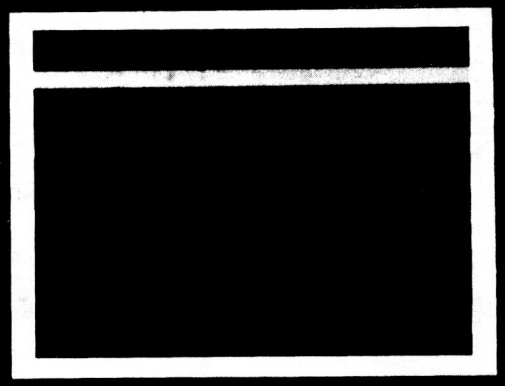
Focal Plane Hybrid Packaging



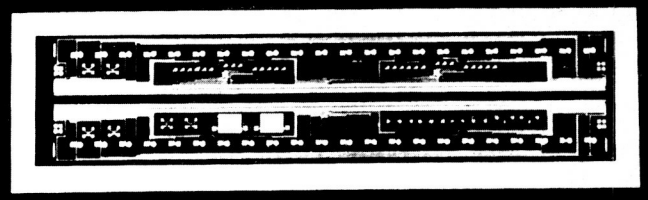
Two Butted SWIR Devices



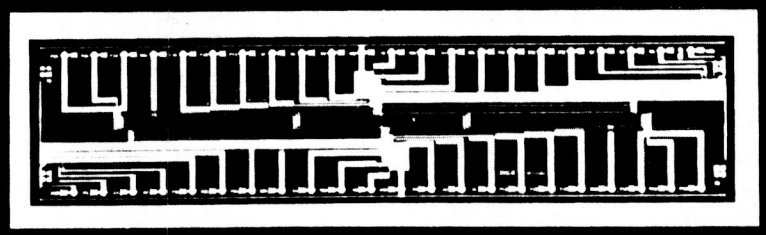
Four Band Visible Filter



Two Band SWIR Device

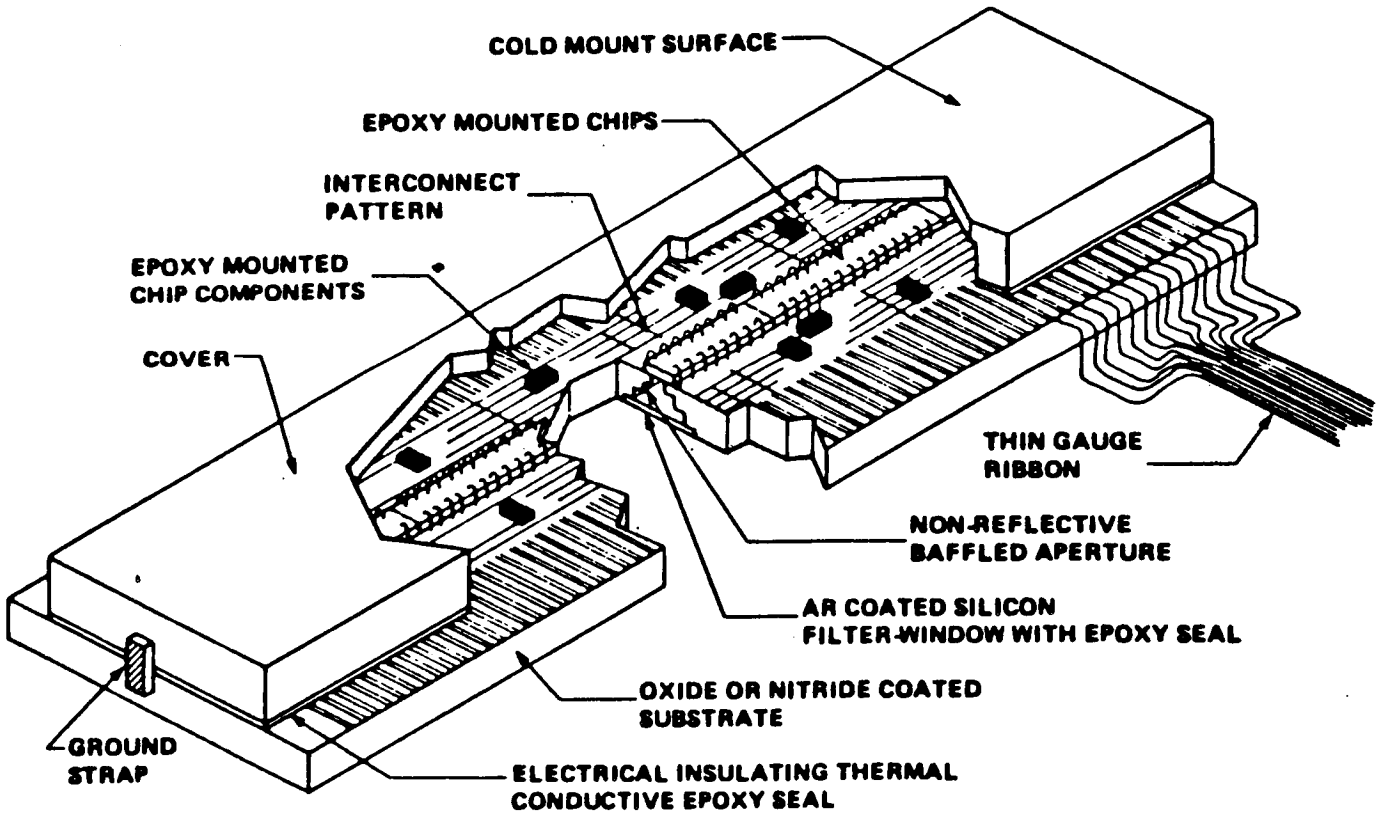


Four Band Visible Device



RCA Advanced Technology Laboratories

88-01

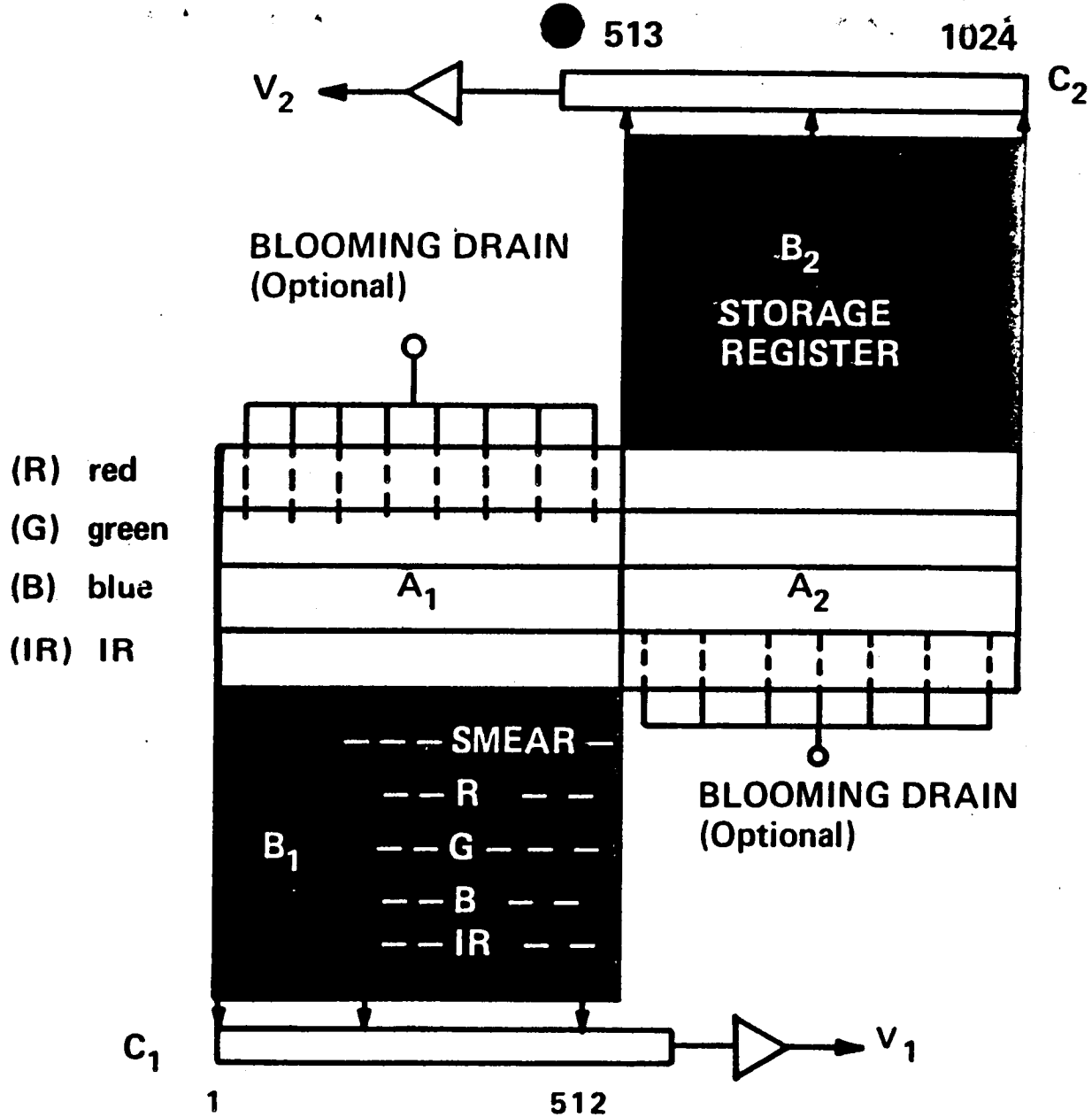


MLA focal-plane packaging concept.

10-89

For remote sensing in the visible (blue, green, red) and near-infrared (700 to 900 nm) spectral bands a 4 x 1024-element image sensor with 15 x 15-μm^2 pixels has been developed. This CCD imager has a dual frame-transfer-type organization designed for buttable construction. This imager has been fabricated with the 3-phase triple-polysilicon-buried-channel CCD technology and laminated construction for back-side illumination that has been developed for the 403 x 512 visible imager.

10-90



VIS/NIR Chip Architecture

10-91

10-92

This table summarizes the four-band VIS/NIR sensor design.

Four-band Visible Sensor Design

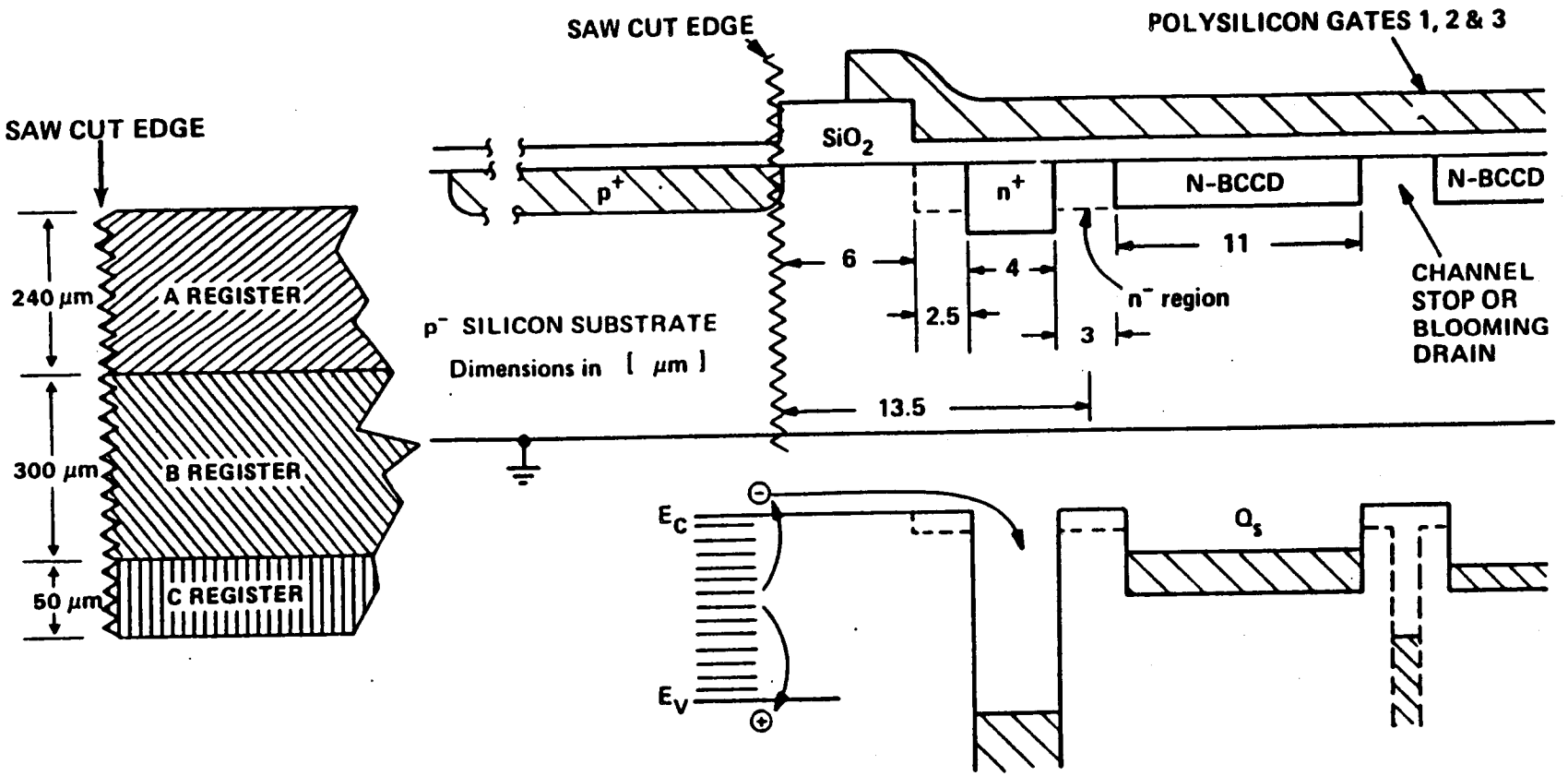
Number of Pixels	4x1024
Pixel Size	15 μ x 15 μ
Cross-Track Spacing	15 μ
Along-Track Spacing	60 μ
Fill Factor	≈ 90%
Dark Current (25° C)	2 nA/cm^2
Horizontal Clock	2 MHz @ 1000 F/S
Optical Integration Time	1 to 4 msec (nominal)
Noise Floor	≈ 50 e rms
Pixel Loss at Seam	2
MTF at Nyquist Frequency	>60% @ 600 nm
X, Y, Z Alignment Tolerances	<5μ/chip
Power Dissipation	67 mW @ 1000 F/S

10-93

10-94

The 4 x 1024-element VIS/NIR chips are fabricated with an edge passivation structure that protects the active sensor area from a leakage current generated at the saw-cut edge.

Edge Passivation Structure



10-95

10-96

This table summarizes the measured performance characteristics of the 4 x 1024 VIS/NIR imager.

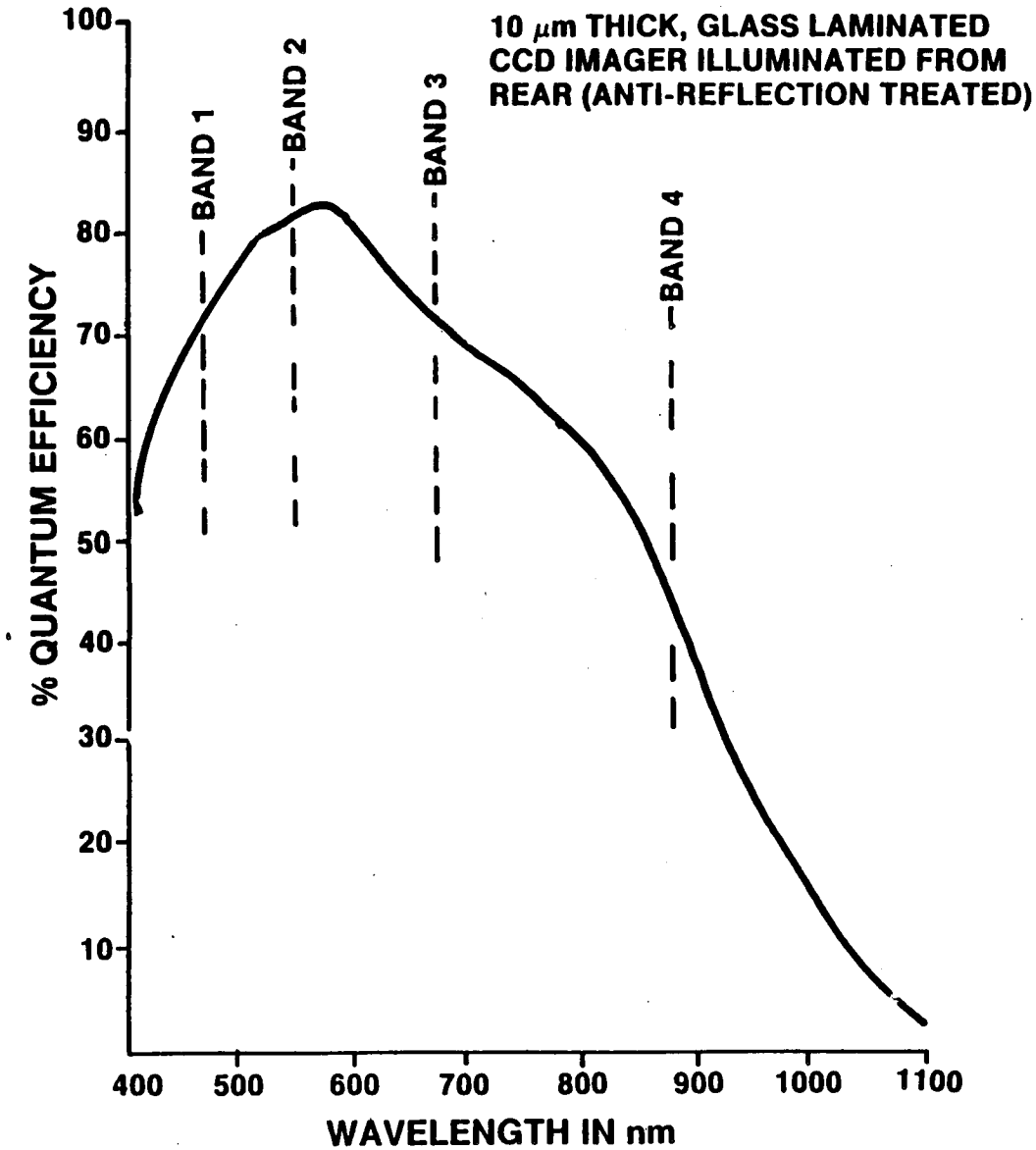
PERFORMANCE

- $\epsilon = 1.3 \times 10^{-5}$
- VERTICAL CROSS TALK = 0.5%
- HORIZONTAL CROSS TALK = 5%
- INTEGRATION TIME = 2 ms
- READOUT CLOCK RATE = 1.52 MHz
- FIELD TRANSFER TIME = 6 μs
- FULL WELL = 1×10^6 ELECTRONS
- BACKGROUND DARK CURRENT
  $\cong$ 100 ELECTRONS/PIXEL AT 23°C

10-97

86-01

Measured spectral response of the four bands of the VIS/NIR sensor with 10 μm thick silicon substrate laminated on a glass substrate.

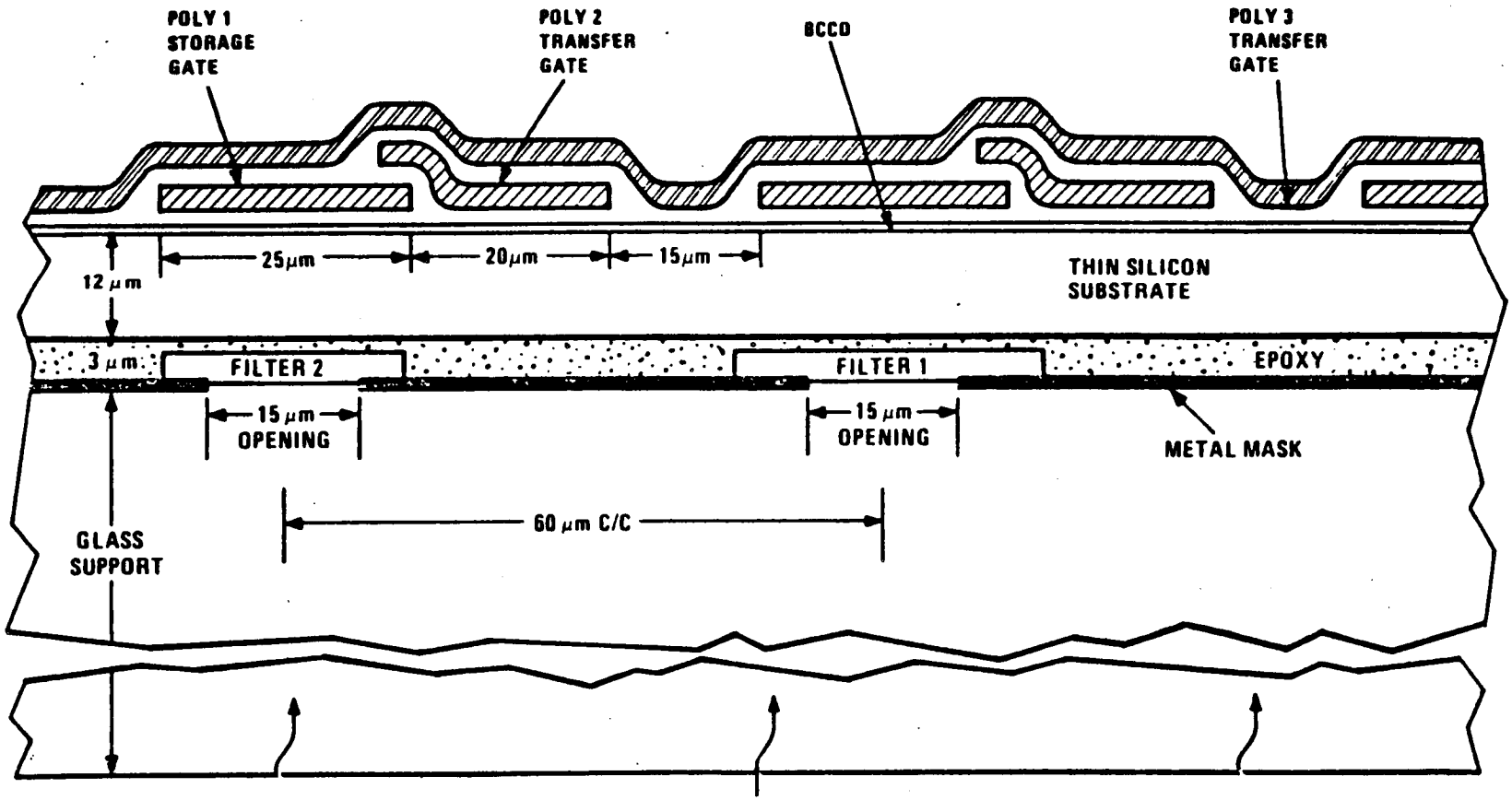


Spectral Response of VNIR CCD Imager

10-99

Cross-sectional view of the VIS/NIR CCD/filter assembly laminated on a glass substrate.

Cross Section of Laminated CCD/Filter Assembly



10-102

Summary of characteristics of the Schottky-barrier IR-CCD arrays developed at RCA.

SCHOTTKY-BARRIER IR-CCD FPAs

- PtSi DETECTORS
  - 3 TO 5 μm SPECTRAL BAND (MWIR)
  - 80K OPERATING TEMPERATURE
  - QUANTUM EFFICIENCY OF 2.0% AT $\lambda = 4.0\ \mu m$
  - NEΔT <0.1K FOR f/3.0 AND 60 FRAMES/S
- Pd_2Si DETECTORS
  - 1 TO 3 μm SPECTRAL BAND (SWIR)
  - 120 TO 140K OPERATING TEMPERATURE
  - QUANTUM EFFICIENCY IN SWIR BAND OF 1.0 TO 10%
- VERY LOW RESPONSE NON-UNIFORMITY (<0.5% RMS)
  - COMPLEX SIGNAL PROCESSING NOT REQUIRED
- RESPONSE CHARACTERISTICS
  - LARGE DYNAMIC RANGE (10^3 TO 10^4)
  - NO OPTICAL CROSS TALK (HIGH MTF)
  - NO LAG
  - NO BLOOMING
- SILICON VLSI PROCESS
  - LOW PRODUCTION COST FOR LARGE VOLUME
  - THE MOST PROMISING IR FPA TECHNOLOGY FOR HIGH-RESOLUTION LARGE-AREA FPAs

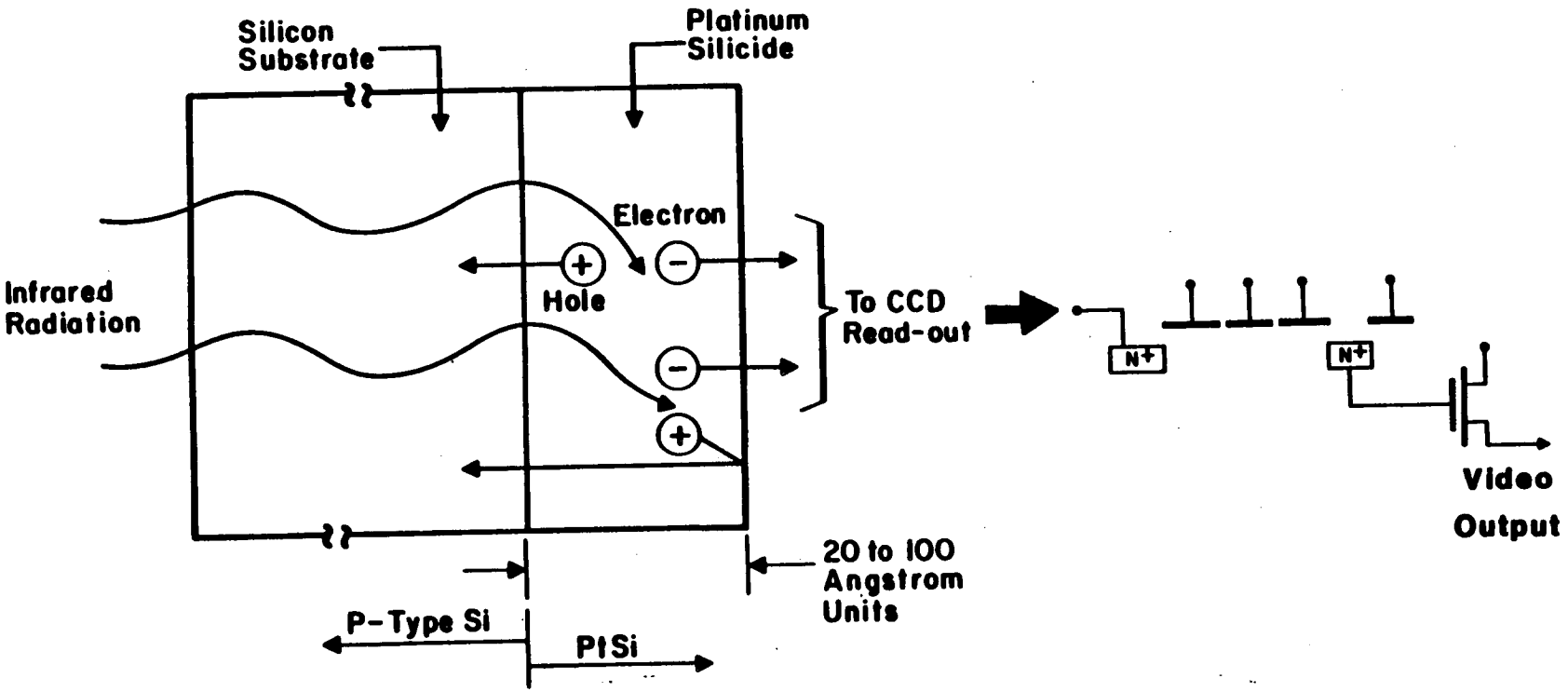
10-103

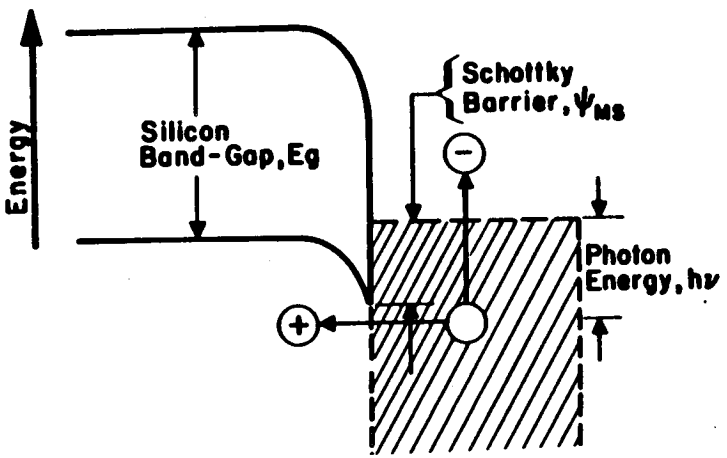
The basic construction and operation of a back-illuminated PtSi Schottky-barrier infrared detector integrated with a silicon CCD readout is illustrated in this figure. The infrared radiation with photon energies less than the band gap of silicon (Eg = 1.1 eV) is transmitted through the substrate. The absorption of the infrared radiation in the silicide layer results in the excitation of photocurrent across the Schottky barrier (Ψ_{ms}) by internal photoemission. The "hot" holes (those that have sufficient energy to to over the Schottky barrier, Ψ_{ms}, formed between the silicide and the p-type silicon) are injected into the silicon substrate. Hence, a net negative charge will accumulate on the silicide electrode. Finally, the detection of the infrared optical signal is completed by transferring into a CCD readout structure this negative charge formed at the silicide electrode. This transfer is carried out either by a periodic voltage reset (vidicon type) readout, or by a continuous (charge-skimming type) readout. The spectral energy window of a back-illuminated Schottky-barrier detector is

$$\Psi_{ms} < h\nu < Eg.$$

where Ψ_{ms} is the metal-semiconductor Schottky barrier,
$h\nu$ is the photon energy, and
Eg is the silicon bandgap energy (1.1 eV).

OPERATION OF SCHOTTKY-BARRIER DETECTOR





$$\psi_{MS} < h\nu < E_g$$

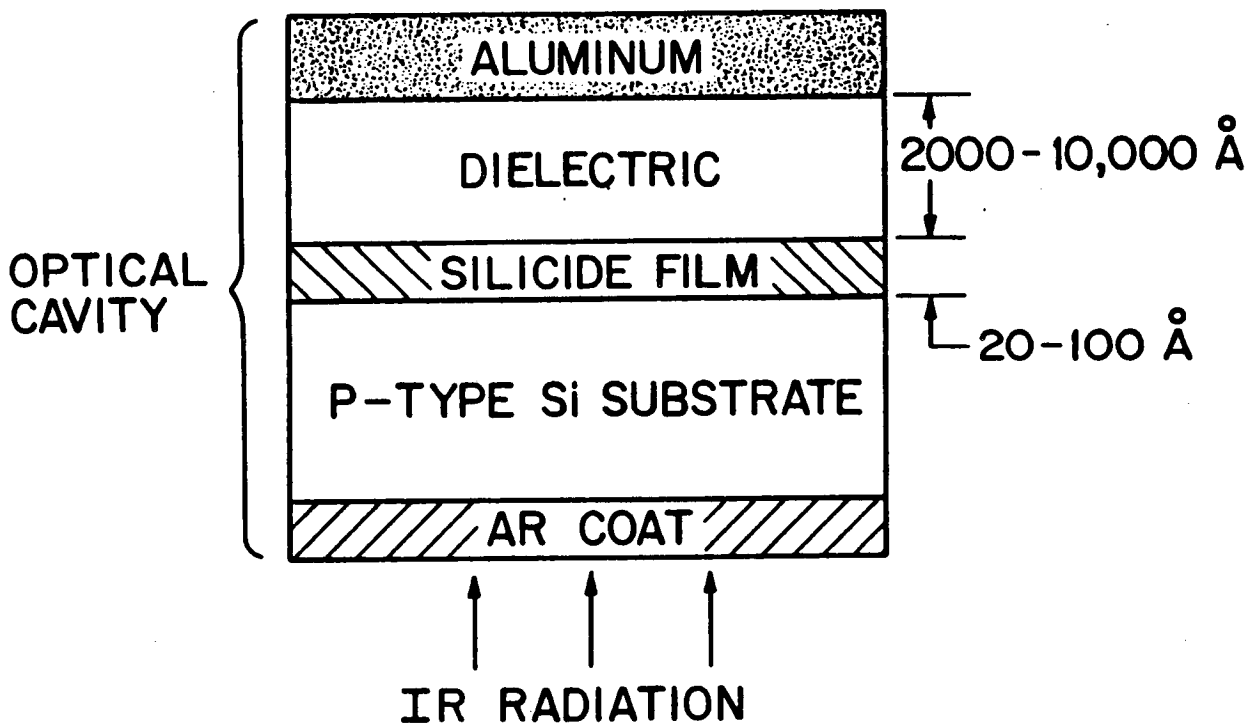
Schottky Barrier < Photon Energy < Silicon Band-Gap

10-105

Construction of Schottky-barrier detector with optical cavity

The construction of the high-performance Schottky-barrier detector (SBD) in the form of a thin-film PtSi with an optical cavity is illustrated in this figure. The SBDs are formed at the end of the fabrication cycle of the IR-CCD arrays. The SBD contact openings are made after the CCD structure is completed except for the aluminum interconnects. Then, a very thin (20 to 100Å) and very uniform film of PtSi is formed on the p-type silicon substrate. The SBD structure with optical cavity is then completed by the deposition a suitable dielectric to separate the PtSi film from the aluminum reflector. Finally, an AR coat is deposited on the backside of the silicon substrate, which increases the coupling of the IR radiation into the SBD by about 30%. The above SBD structure is designed to induce (1) an enhanced optical absorptance as a result of multiple pass of the light in the film and (2) an increase in the injection (emission) efficiency of hot holes into the substrate.

Cross-sectional view of thin-PtSi SBD with optical cavity.



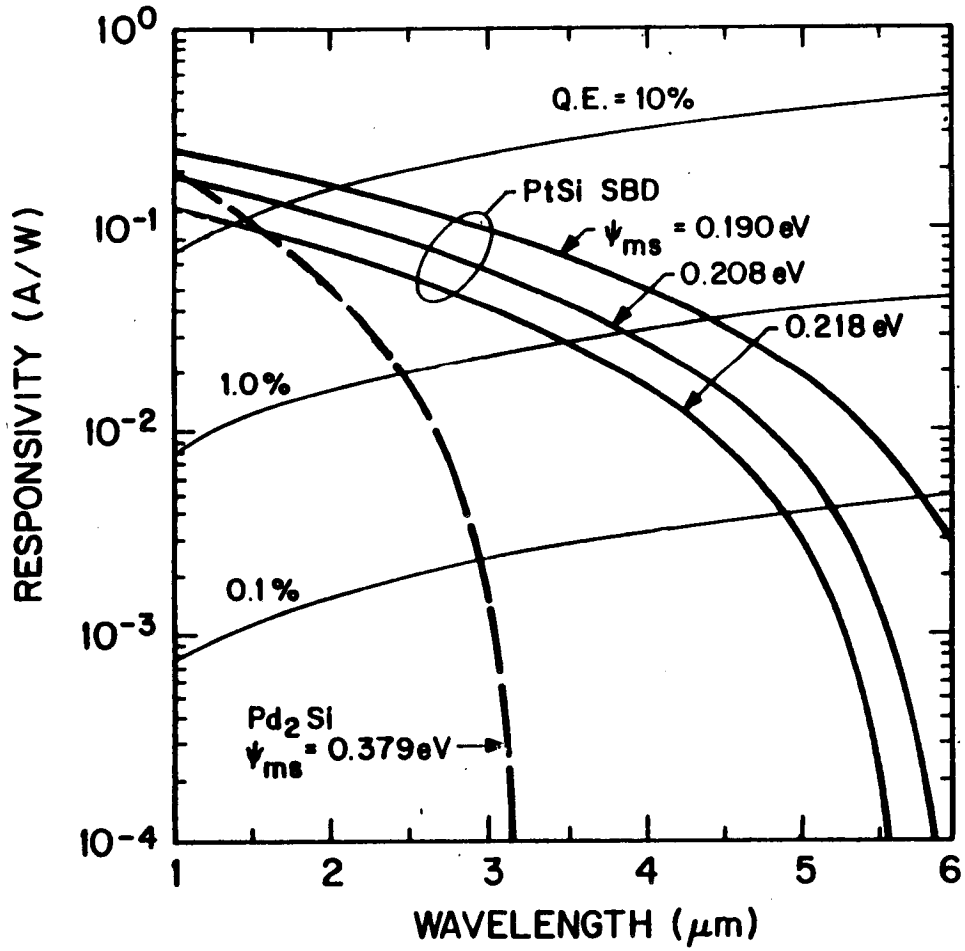
10-107

Measured responsivity and quantum efficiency (Q.E.) of PtSi and Pd_2Si Schottky-barrier detector arrays developed at RCA.

10-108

RCA

Responsivities of PtSi and Pd_2Si Schottky-Barrier Detectors



10-109

For remote sensing in the short wavelength infrared (SWIR) spectral bands (1.24, 1.65, and 2.22 μm) RCA developed a 2 x 512-element linear imager sensor with 30 x 30-μm^2 pixels that has been fabricated either with Pd_2Si or PtSi Schottky-barrier detectors (SBDs). With Pd_2Si SBDs this imager can be operated with passive cooling at a temperature of 120K and has a quantum efficiency of 10% and 4% at wavelengths of 1.24 and 2.22 μm, respectively.

- This table summarizes the design of the dual band SWIR sensor.

10-110

RCA

Dual Band SWIR Sensor Design

NUMBER OF DETECTORS	2 X 512
CROSS-TRACK SPACING	30 μ
ALONG-TRACK SPACING	300 μ
FILL FACTOR	70-85%
OPERATING TEMPERATURE	125K
DARK CURRENT (120K)	2 nA/cm^2
OPTICAL INTEGRATION TIME	1 to 4 msec (nominal)
NOISE FLOOR	$\approx$ 100 e rms
PIXEL LOSS AT SEAM	2
MTF AT NYQUIST FREQUENCY	65%
X, Y, Z ALIGNMENT TOLERANCES	$<$ 5 μ/CHIP
POWER DISSIPATION	18 mW

A 3-inch silicon wafer contains 42 chips of the 2 x 512 SWIR IR-CCD imagers.

10-112

RCA

NASA SWIR 3" Wafer

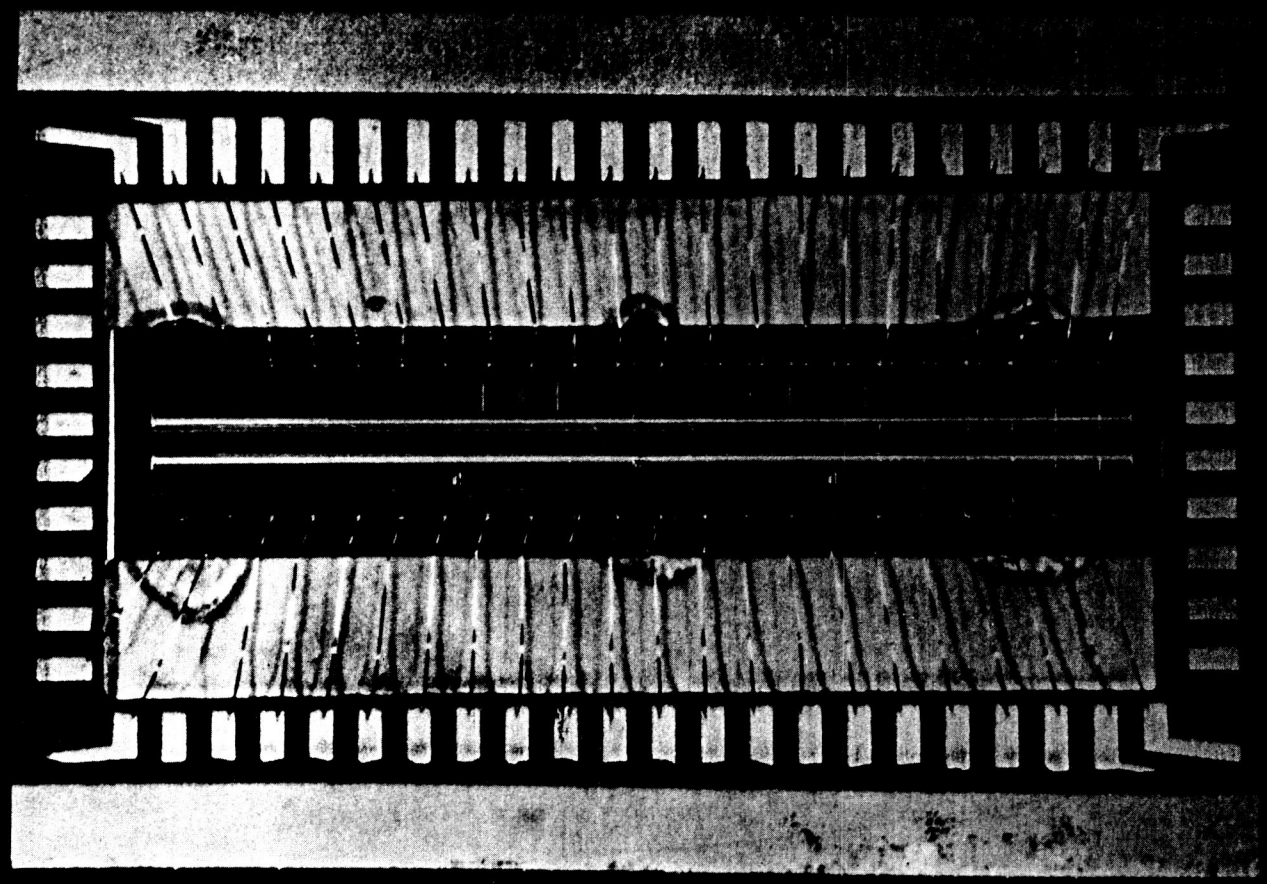
- 42 DEVICES PER WAFER
- EACH DEVICE 605 MILS X 146 MILS

10-113

10-114

This photograph shows a 2 x 512 Pd_2Si IR-CCD array bonded in a ceramic package.

Packaged NASA Dual Band Sensor

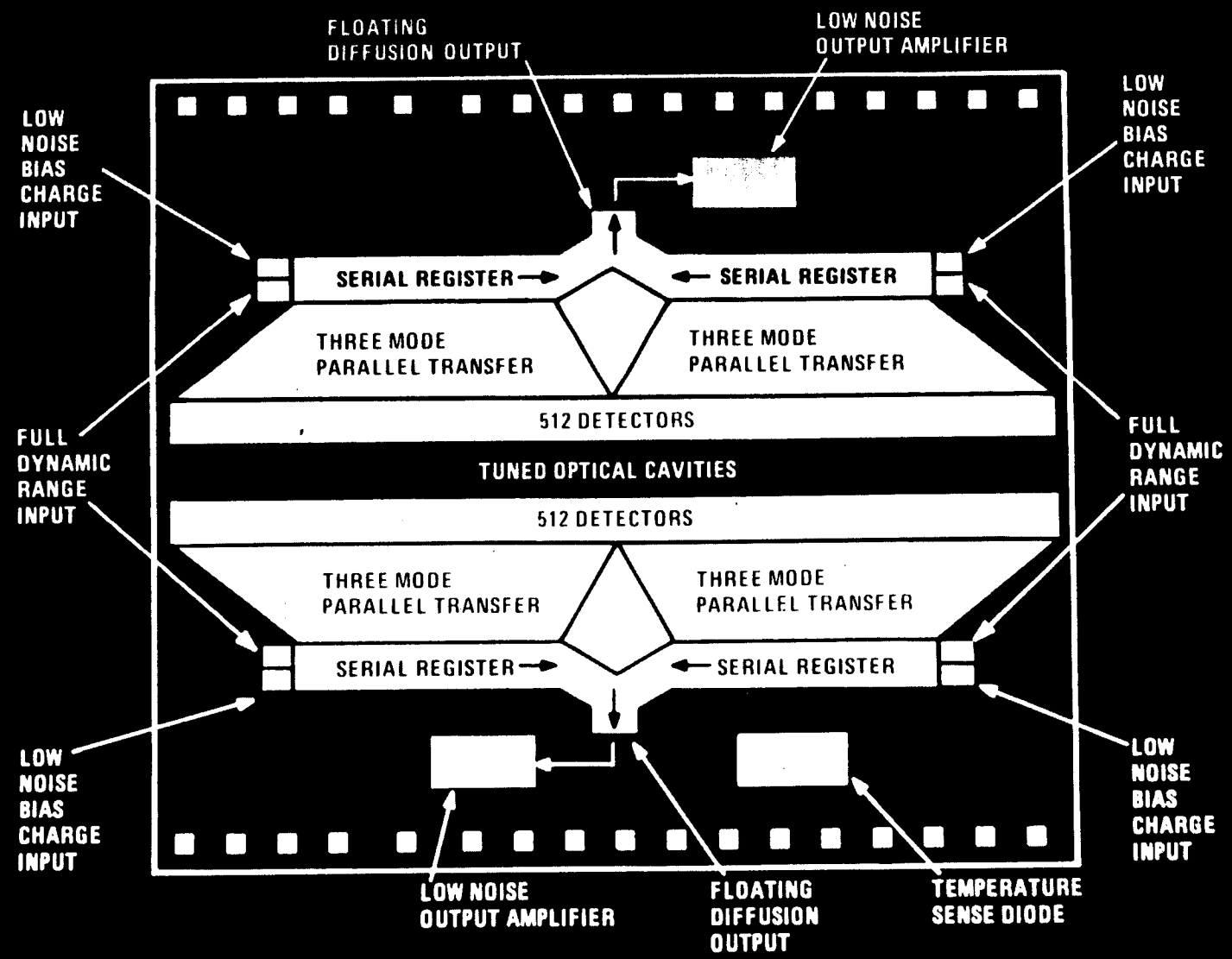


- TWO 512 DETECTOR LINEAR ARRAYS
- Pd_2 Si DETECTORS FOR SWIR OPERATION
- OPERATING TEMPERATURE 125K

10-116

Architecture of the 2 x 512 SWIR MLA chip designed for buttability and low power dissipation.

Dual Band Sensor Design



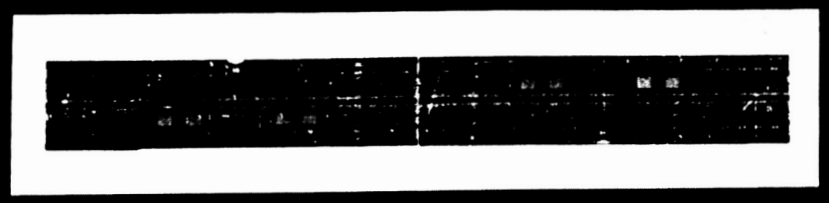
First samples of two butted 2 x 512 SWIR devices with a loss of 2 to 4 detectors at the seam.

10-118

RCA

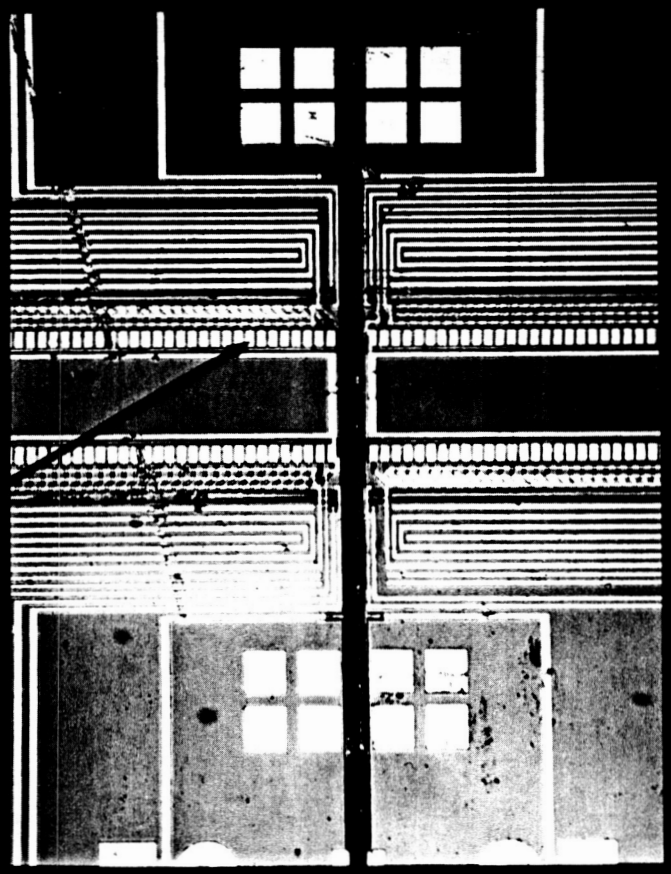
First Sample of Butted Devices

TWO SWIR DEVICES



1.2″

3–4 DETECTOR LOSS AT SEAM



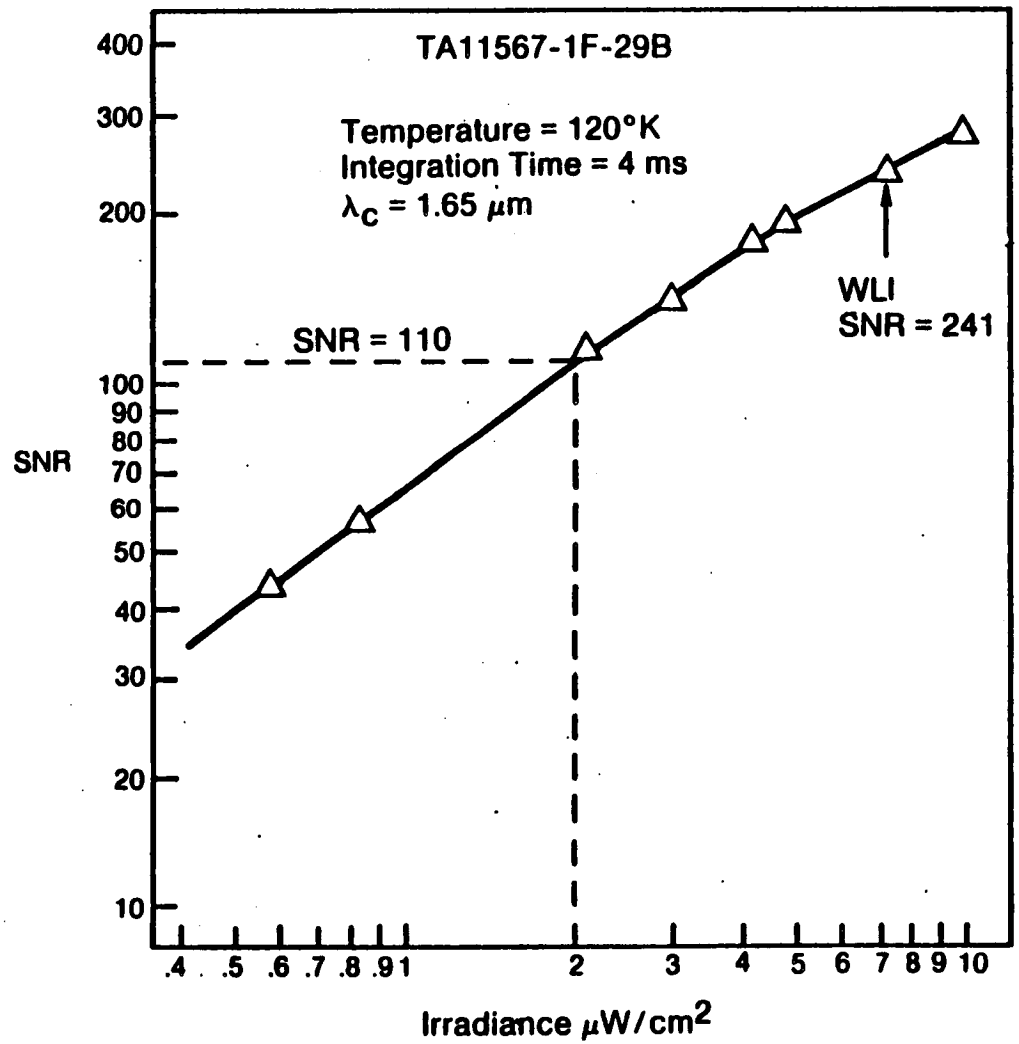
DETECTOR

10-119

Signal-to-noise ratio (SNR) of 241 was achieved at the Working Level Irradiance (WLI) of 7.2 $\mu W/cm^2$ and SNR of 110 at 2.0 $\mu W/cm^2$ for the 2 x 512-element Pd_2Si IR-CCD sensor with 200 nm bandpass filter centered at a wavelength of 1.65 μm operating at a temperature of 120K with integration time of 4.0 ms.

10-120

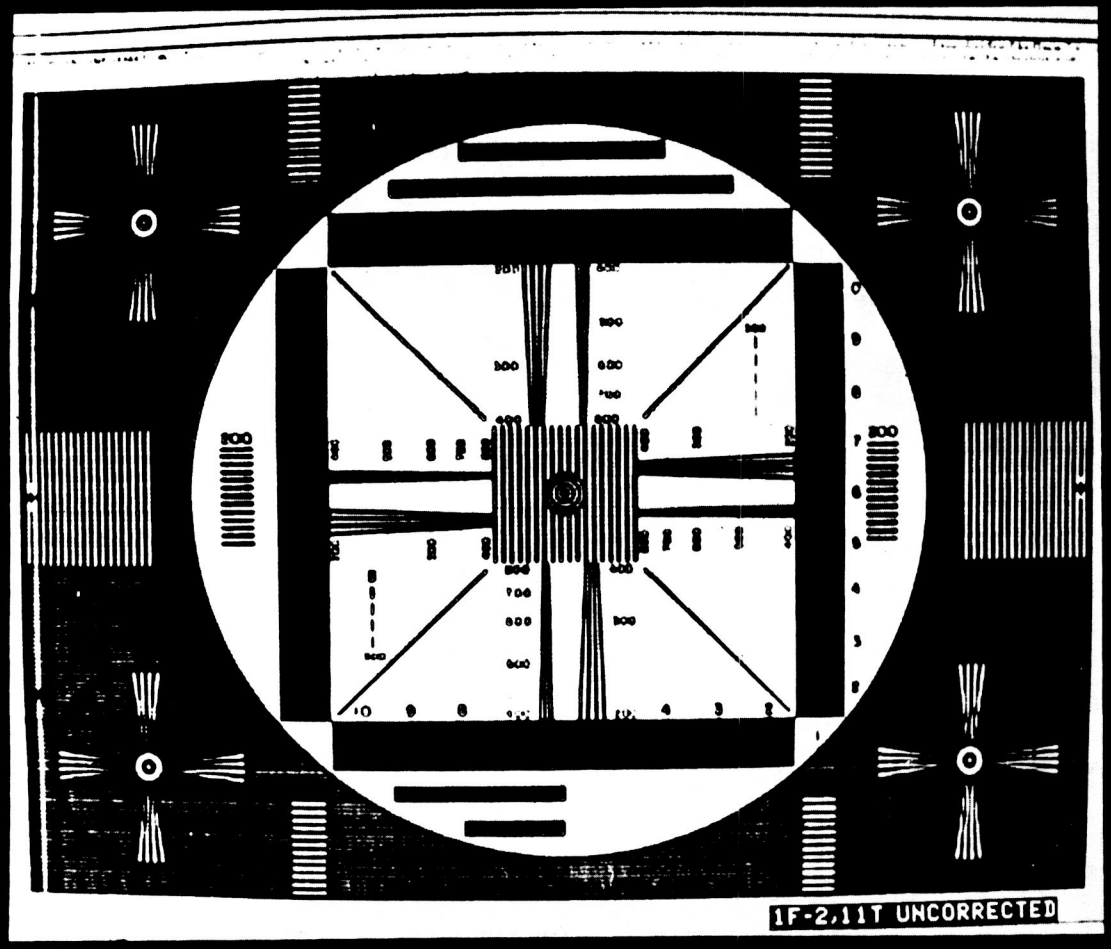
MEASURED SNR AS FUNCTION OF IRRADIANCE FOR 2×512 Pd2Si IR - CCD LINE SENSOR



10-121

Uncorrected image of a standard resolution pattern detected with the 512-element Pd_2Si CCD line sensor operated with 200 nm band-pass filter centered at a wavelength of 1.65 μm. This 512-element line imager had a response non-uniformity of 2% (rms).

SWIR Developmental Imagery



SCAN DIRECTION

- UNCORRECTED IMAGERY
- 3.6 $\mu W/cm^2$ @ 1.65 μm
- 2% RMS NONUNIFORMITY

10-123

10-124

For thermal imaging in the medium wave infrared (MWIR) in the 3 to 5 μm band and operation at temperature of 77 to 80K we have developed a 160 x 244-element interline-transfer IR-CCD image sensor with PtSi SBDs. This staring IR imager has 80 (H) x 40 (V)-μm^2 pixels and is constructed for operation with two vertically interlaced fields per frame. Excellent quality thermal imaging and noise equivalent temperature (NEΔT) of less than 0.1K were demonstrated with the 160 x 244 IR-CCD imager opeating with standard TV frame rate of 30 frames/s, f/2.35 optics, and a one-point uniformity corrector that averages 16 background frames to form the reference frame subtracted from the imager video output.

Characteristics of 160 x 244-Element Schottky-Barrier IRCCD FPA

- 80 (H) x 40 (V)-μm^2 PIXELS WITH 39% FILL FACTOR
  - 4 (H) x 3 (V) ASPECT RATIO
- PtSi SCHOTTKY-BARRIER DETECTORS
  - FOR 3 TO 5 μm MWIR BAND
- 584 x 464-mil^2 CHIP AREA
- ONE-POINT UNIFORMITY RESPONSE CORRECTOR
  - AVERAGES UP TO 16 REFERENCE FRAMES WITH 12-BIT ACCURARY
- FOR OPERATION AS STARING IMAGER AT 30 FRAMES/S AND f/2.35 OPTICS
  - GOOD QUALITY THERMAL IMAGING
  - MEASURED NEΔT $<$0.1 K
  - FIXED-PATTERN SPATIAL NOISE IS SMALLER THAN TEMPORAL OUTPUT NOISE

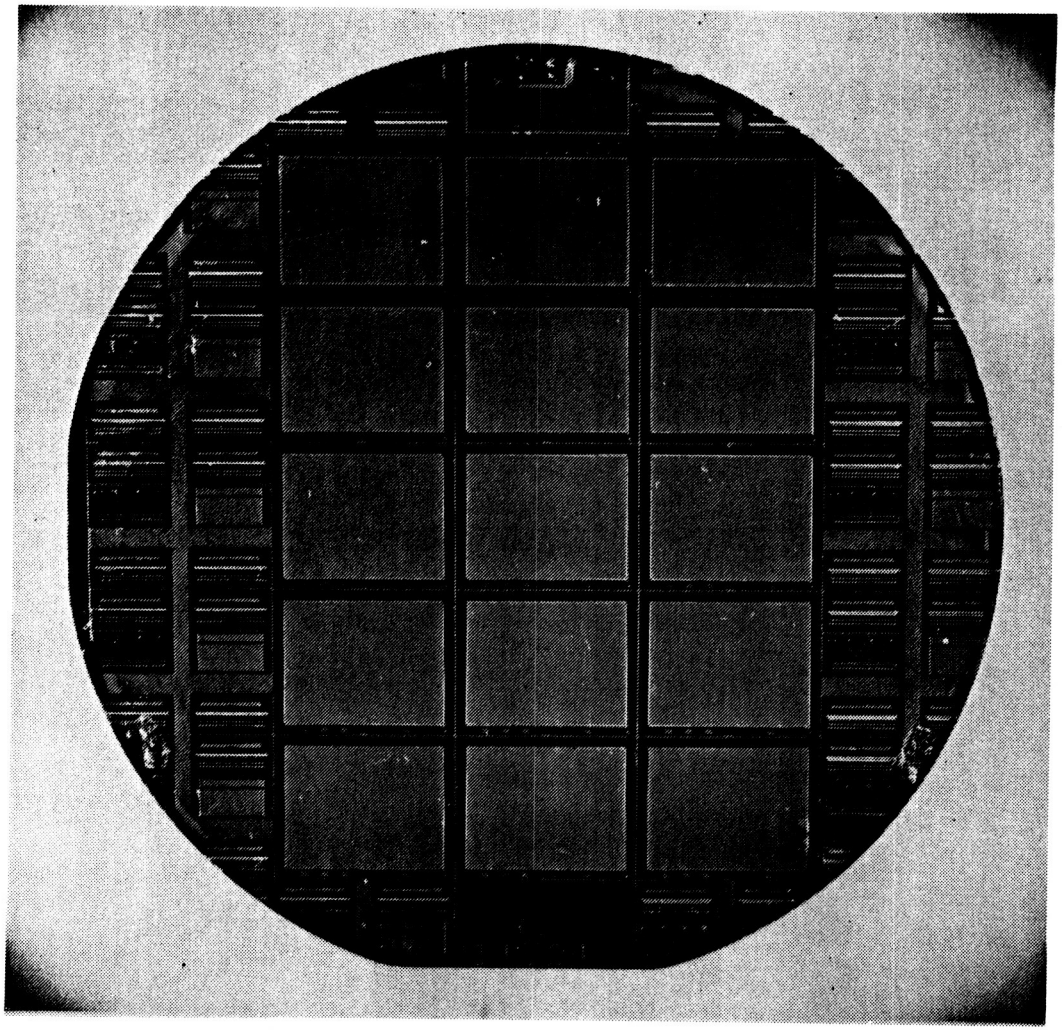
10-125

The 160 (H) x 244 (V)-element imager has 80 (H) x 40 (V)-μm^2 pixels resulting in a standard TV aspect ratio of 4 (H):3. The chip area of this imager is 584 x 464-mil^2. As shown in this figure, a 3-inch silicon wafer contains fifteen 160 x 244 imager arrays and various test arrays around the perimeter.

10-126

RCA

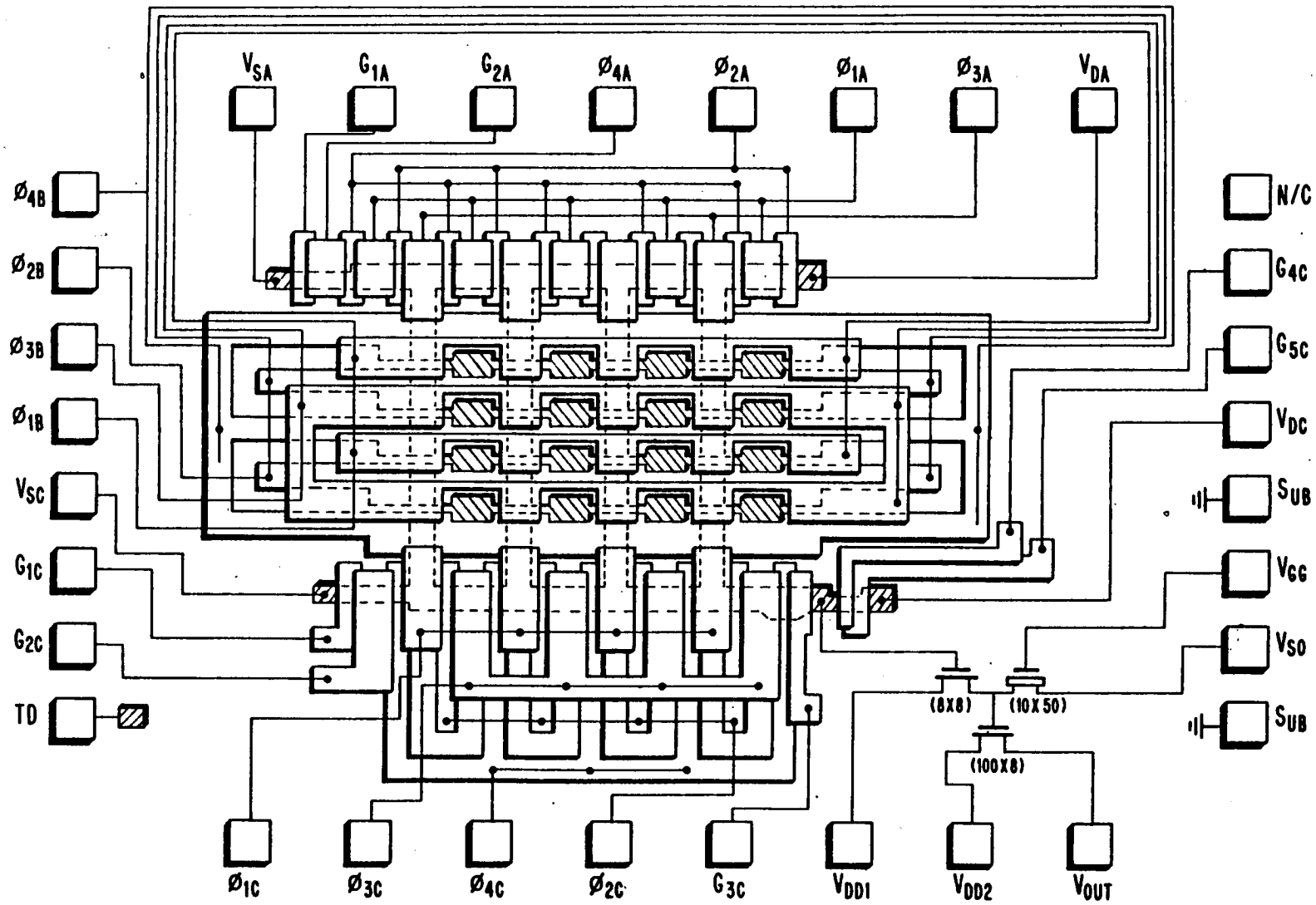
3-INCH SILICON WAFER PROCESSED WITH 160 x 244-ELEMENT PtSi SCHOTTKY-BARRIER IR-CCD IMAGERS (CHIP SIZE = 584 x 464 mil^2)



10-127

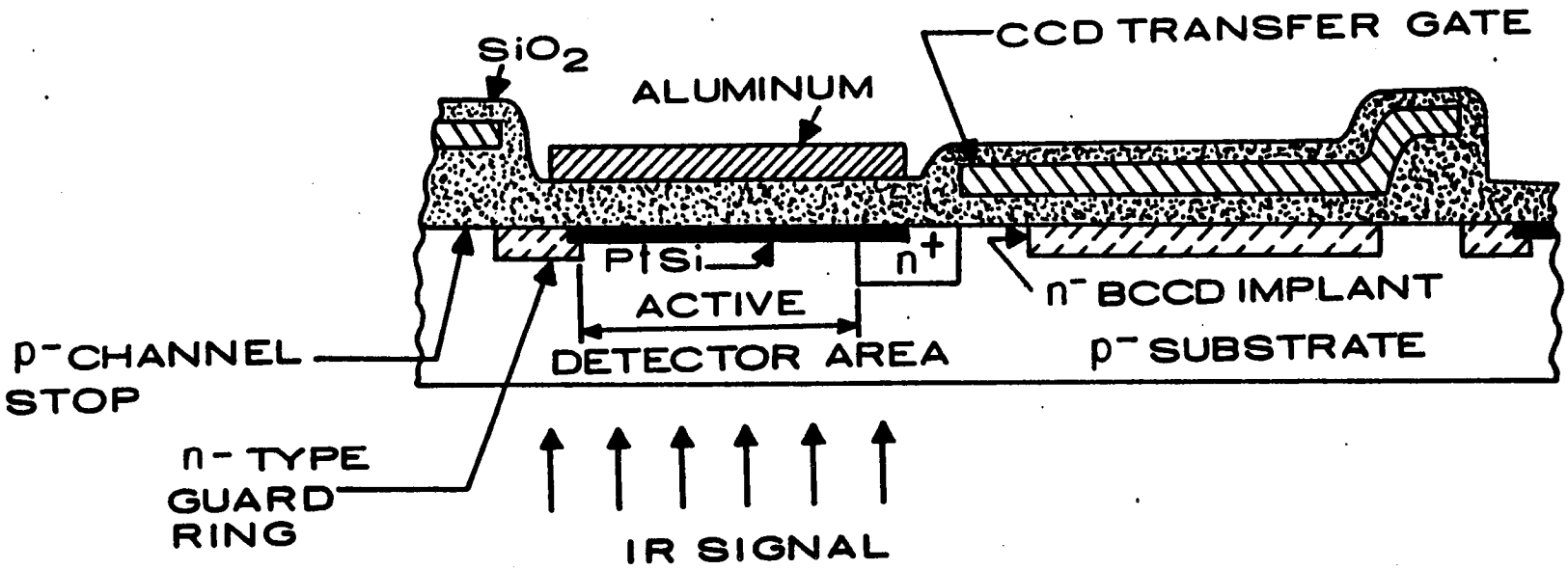
The 160 x 244-element FPA is an interline transfer IR-CCD designed for operation with a readout of two vertically-interlaced fields per frame. A schematic layout with 4 x 4 pixels illustrating the design of this imager is shown in this figure. This design allows a rather area-efficient construction of a 4-phase (double-clocked) IR-CCD array with two-level polysilicon gates. The 160 x 244 IT IR-CCD imager has an input series register (A), a parallel column register (B), and a series output register (C). The input A-register is provided mainly for testing of the CCD array. The output C-register is read out by an on-chip two-stage source-follower amplifier with a floating-diffusion input capacitance of 0.06 pF and output transfer conversion of 700 to 1000 electrons/mV (depending on the biasing conditions).

SCHEMATIC OF 160 X 244 IR-CCD FPA CHIP

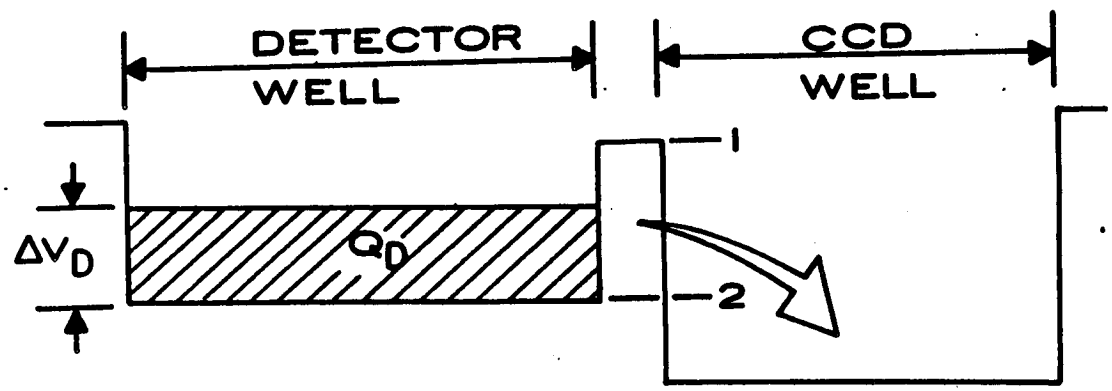


The cross-sectional view of the pixel construction is illustrated in part (a) of this figure. In this construction the SBDs are contained on all four sides by one or two levels of polysilicon gates. To minimize dark-current spikes the PtSi SBDs are surrounded by n-type guard rings which are self-aligned to the polysilicon gates. The channel stops between two adjacent SBDs in the vertical direction and the SBDs and buried-channel CCD (BCCD) readout registers are in the form of p^-, or surface-channel CCD (SCCD), regions. The SCCD channel stops are driven into accumulation by the B-clock ($\Delta\phi_B$) during the CCD-charge-transfer operation of the B-register. At the end of the optical integration time (T_i) the CCD transfer gate ϕ_{1B} (or ϕ_{3B}) is driven to a positive potential. This operation resets the SBD electrode to a reference potential 2 and transfers the detected charge signal (Q_D) into the CCD well. During this charge transfer a higher barrier potential is formed under the thick SiO_2 channel stop. This barrier provides the directionality of the signal-charge flow during the SBD charge readout. The operation of the SCCD channel-stop regions into accumulation assures an operational blooming control mode of the SBDs, provided the BCCD readout register has a sufficient charge-handling capacity.

PtSi SCHOTTKY-BARRIER DETECTOR WITH BCCD READ-OUT



(a)

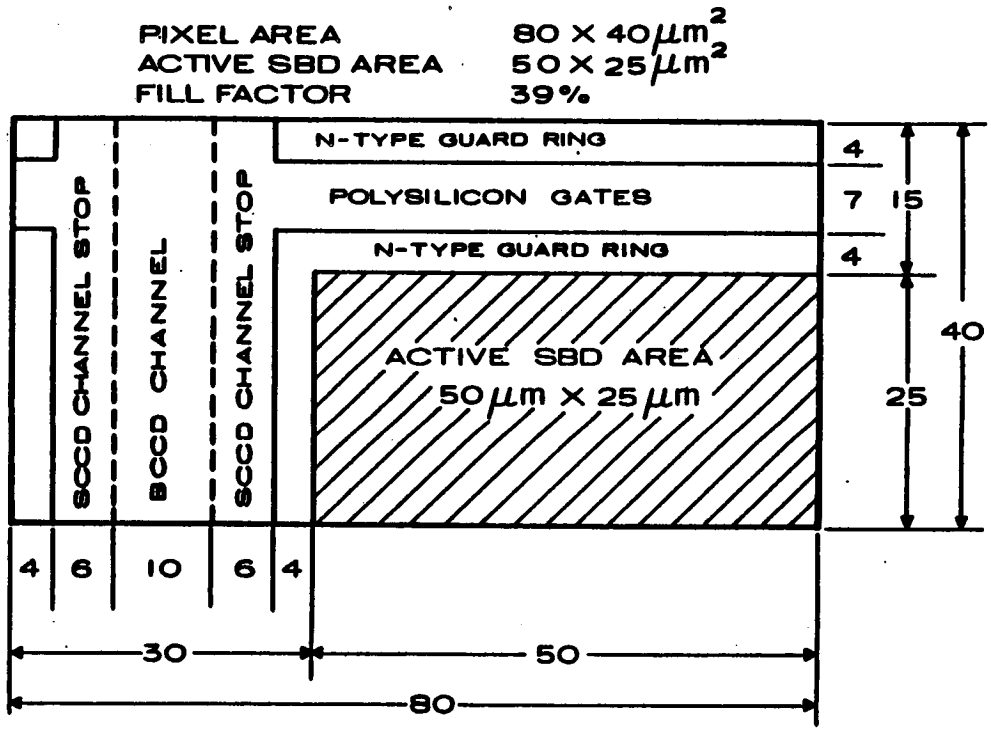


(b)

10-131

This figure illustrates the pixel layout of the 160 x 244 IR-CCD imager. The inactive pixel dimension in the vertical direction is 15 μm. Of this, 7 μm corresponds to the width of two layers of polysilicon lines which form the connections for the CCD gates of the B-register. The additional 8 μm represents the width of two SBD guard rings. The inactive pixel dimension in the horizontal direction is 30 μm. This corresponds to a 10-μm-wide BCCD channel surrounded on both sides by 6-μm SCCD channel stops and 4-μm SBD guard rings. The resulting active detector area is 50 x 25 μm^2. Therefore, for an 80 x 40 μm^2 pixel area, the fill factor of this FPA is 39%.

Simplified pixel layout of 160 x 244 IR-CCD FPA.



10-133

The process and the design of the 160 x 244 IR-CCD FPA were integrated to maximize the fill factor while maintaining a sufficient charge-handling capacity of the BCCD readout register to prevent blooming under intense optical signals, using very conservative design rules for maximizing the IC processing yield for the rather large (584 x 464-mil^2) chip area. This table illustrates the trade-offs between the design rules (represented by the width of the SCCD channel stops, n-type guard rings, and polysilicon lines) and the resulting fill factor. We have found that for our process to assure a sufficient charge-handling capacity of the BCCD register, the area of the half-stage BCCD register must be equal to or greater than 1/5 of the total detector area including the guard rings.

RCA

Fill Factors vs. Design Rules for IT IR-CCD Image Sensors with 80 x 40 μm Pixels

	CHANNEL STOPS (μm)	SBD GUARD RINGS (μm)	POLY-SILICON LINES (μm)	INACTIVE PIXEL DIMENSION		FILL FACTOR (%)
				Horz. (μm)	Vert. (μm)	
IRCCD-1 160 x 244 IRCCD 1983/1984	6	4	7	30	15	39
IRCCD-2 IMPROVED IRCCD-1	5	3	6	26	12	47
IRCCD-3 FOR 10X STEPPER	3	2	5	21	9	57
IRCCD-4 VLSI PROCESS	2	1	3	18	5	68

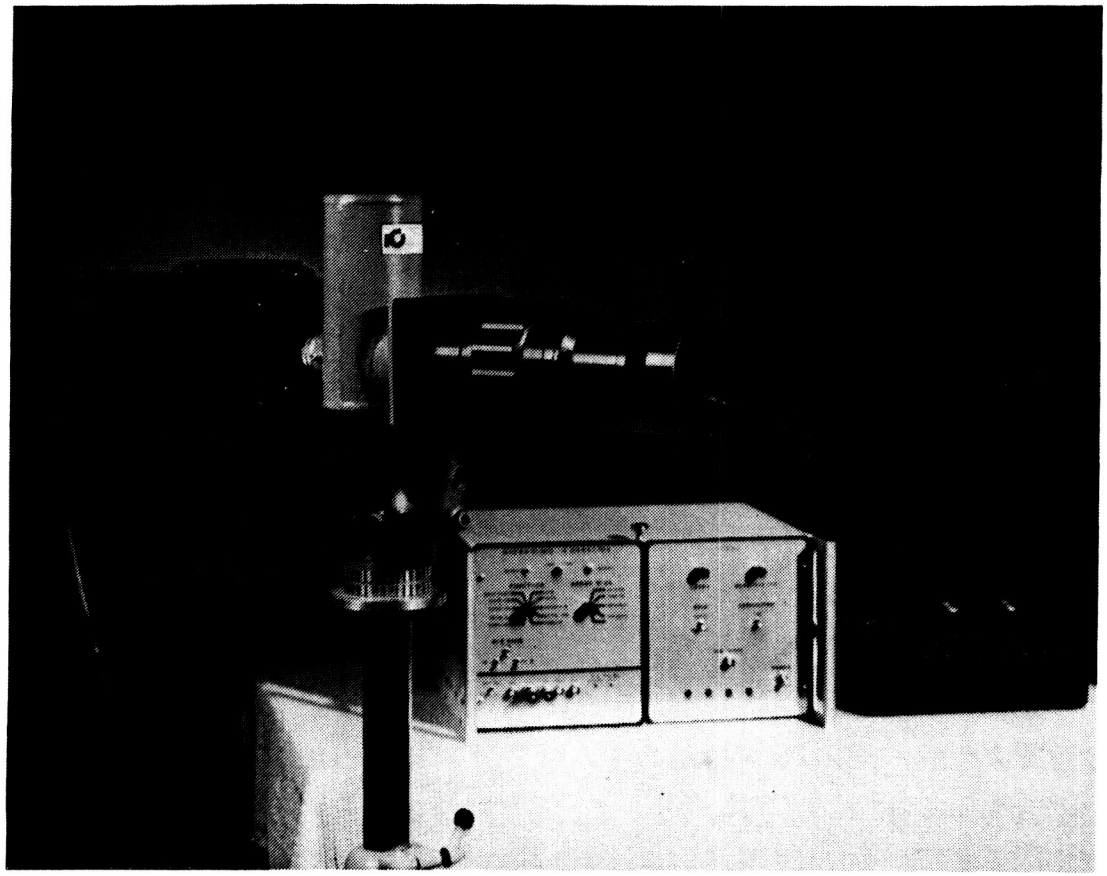
10-135

The performance of the 160 x 244 PtSi IR-CCD imagers was evaluated with the IR TV camera shown in this figure. The IR imager bonded in the 32-pin ceramic package is cooled to about 77K by a liquid-nitrogen Dewar. The camera electronics including all of the timing and driver circuits are contained in the enclosure next to the Dewar. The black terminal panel (on the right side) contains all of the controls for the camera waveforms and DC voltages required for operation of the IR-CCD imager. The electronics box to the right of the IR-CCD camera is an off-set-type one-point response uniformity corrector. This uniformity corrector forms a reference frame (that is subtracted from each video signal frame) by averaging up to 16 background-exposure frames. The IR-CCD camera operates with 30 160 x 244-element frames/s and two vertically-interlaced 160 x 122-element fields/frame. It produces a standard TV video output with horizontal line time of 63.5 microseconds and imager output signal at every second horizontal TV line. The total video frame time (including the vertical blanking time) corresponds to two identical (uninterlaced) fields each with 263 horizontal TV lines. During the readout of the 160 x 244-element imager frame, the odd field contains the imager readout of the 122 odd lines (i.e., 1, 3, 5,... 243) and the even field contains signal from the 122 even lines (i.e., lines 2, 4, 6,...244).

10-136 C4

RCA 160 X 244-ELEMEMENT IR-CCD TV CAMERA

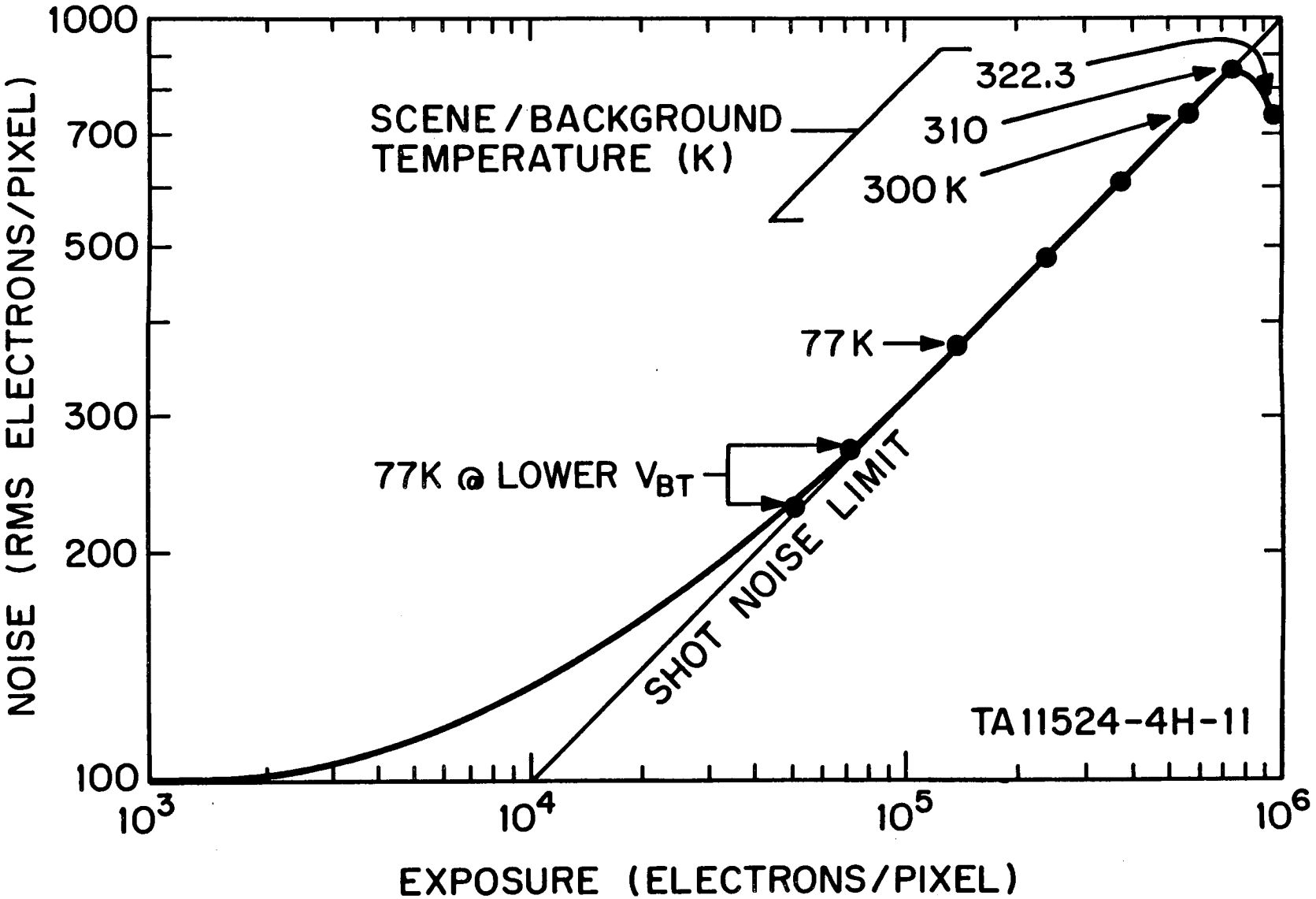
- PtSi SCHOTTKY-BARRIER DETECTORS
- 30 FRAMES/S WITH std. TV INTERLACE
- F/2.35 OPTICS AND 3.4 μm CUT-ON FILTER
- ONE-POINT UNIFORMITY CORRECTOR AVERAGING UP TO 16 REFERENCE FRAMES



RCA

NOISE CHARACTERISTICS OF 160 X 244 ELEMENT IR-CCD IMAGE SENSOR

(80 X 40 μm^2 PIXELS, 30 FRAMES/S, f/2.5 OPTICS



10-138

For the day-time and night-time thermal imaging illustrated in this figure, the 160 x 244 IR-CCD TV camera was operated at 30 frames/s with standard TV field interlace, with a 175 mm f/2.35 lens, f/2.0 cold shielf, a long-pass filter having a cut-on wavelength of 3.4 μm, and a one-point uniformity corrector that substructs a reference frame (obtained by averaging 16 background frames) from the video output.

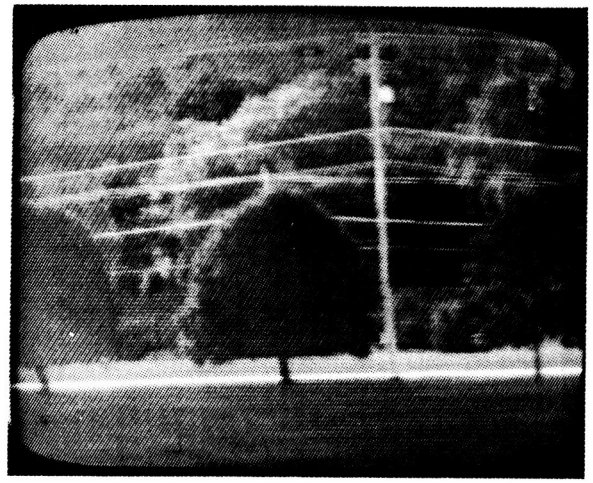
For operation without the uniformity corrector, the measured low-frequency spatial non-uniformity of the imager due to the f/2.0 cold-shield shading is in the range of 5 to 10% of the 300K background signal. The corresponding measured high-frequency spatial non-uniformity for 300K background for the 160 x 244 IR-CCD imagers is in the range of 1.0 to 2.0% rms before the uniformity correction. However, for operation with the one-point off-set-type uniformity corrector averaging 16 reference frames, the rms non-uniformity is less than 0.18% and corresponds to less than 50% of the temporal output noise.

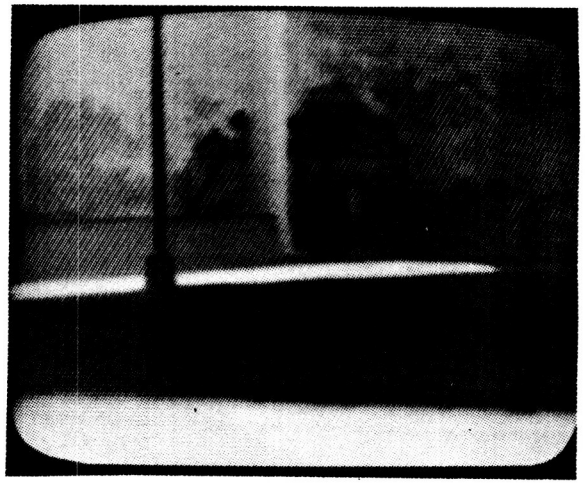
10-139

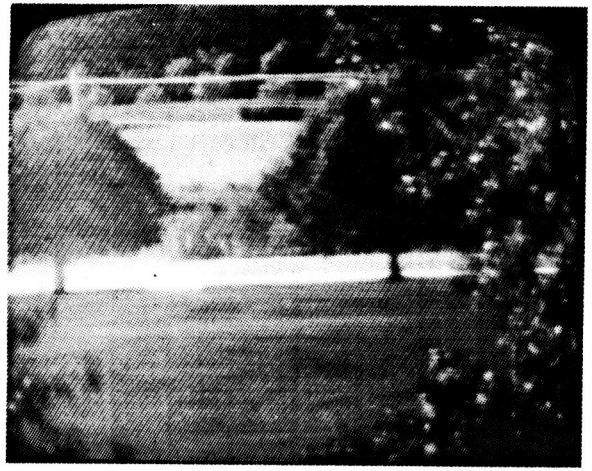
RCA

THERMAL IMAGE DETECTED BY 160 x 244-ELEMENT PtSi SCHOTTKY-BARRIER IR-CCD IMAGER

(OPERATING AT 30 FRAMES PER SECOND WITH STANDARD TV INTERLACE)







DAY

NIGHT

10-140

RCA

Acknowledgement

THE DEVELOPMENTS OF THE VIS/NIR AND SWIR MLA IMAGERS WAS SUPPORTED BY NATIONAL AERONAUTICS AND SPACE ADMINISTRATION, GODDARD SPACE FLIGHT CENTER, GREENBELT, MD UNDER CONTRACTS NASS-27505 AND NASS-27800 WITH ADVANCED TECHNOLOGY LABORATORIES, RCA GOVERNMENT SYSTEMS DIVISION, MOORESTOWN, NJ.

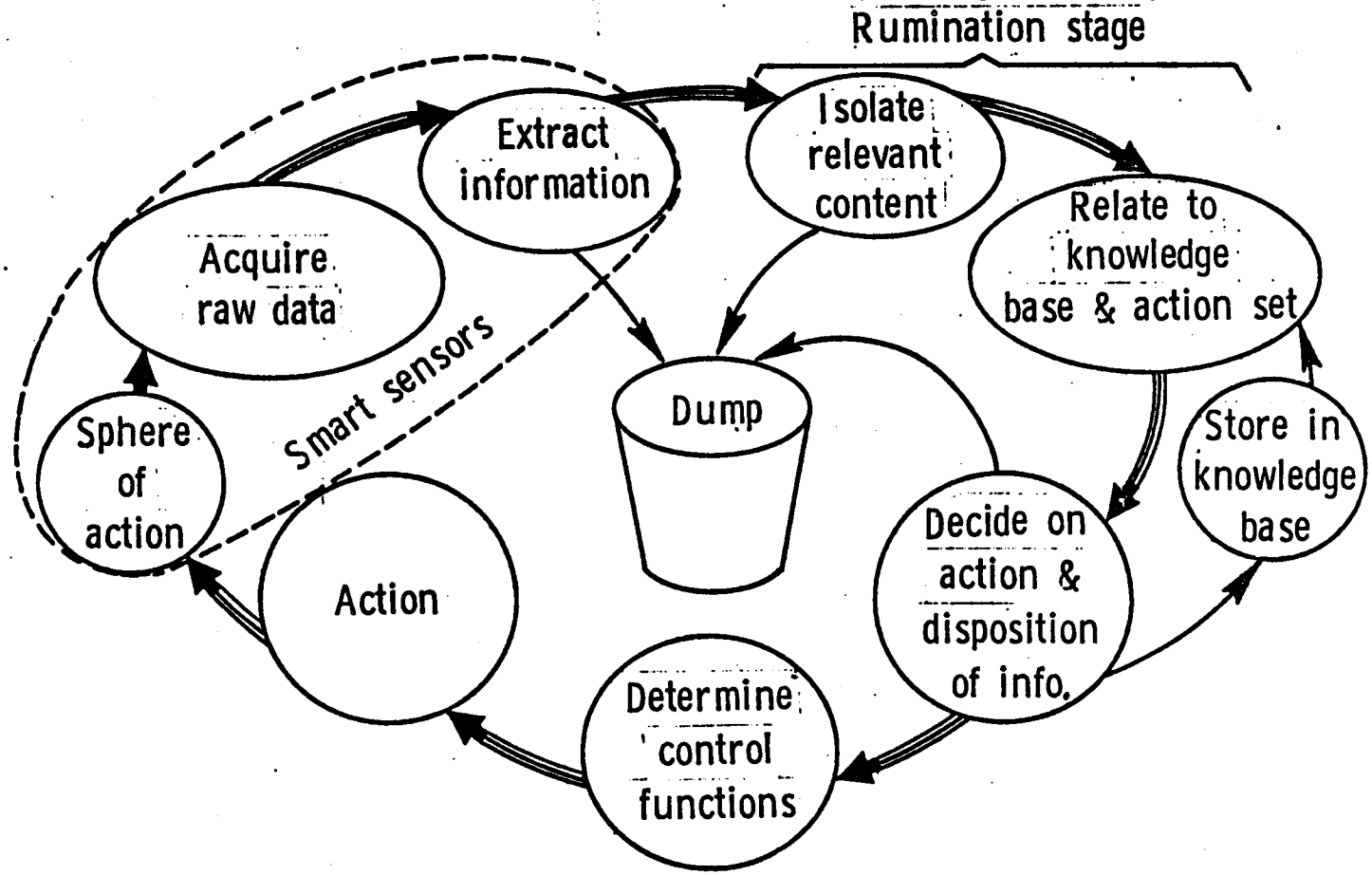
THE DEVELOPMENT OF THE 160 x 244-ELEMENT IR-CCD FPA WAS SUPPORTED BY ROME AIR DEVELOPMENT CENTER, HANSCOM AFB, MASSACHUSETTES, 01731, AND THE ARMY DIRECTED ENERGY DIRECTORATE, HUNTSVILLE, AL, 35898, UNDER CONTRACT NO. F19628-81-C-0108 WITH RCA LABORATORIES, PRINCETON, NJ 08540.

141-01

INTEGRATED SENSING/PROCESSING FOR AUTONOMOUS OPERATIONS

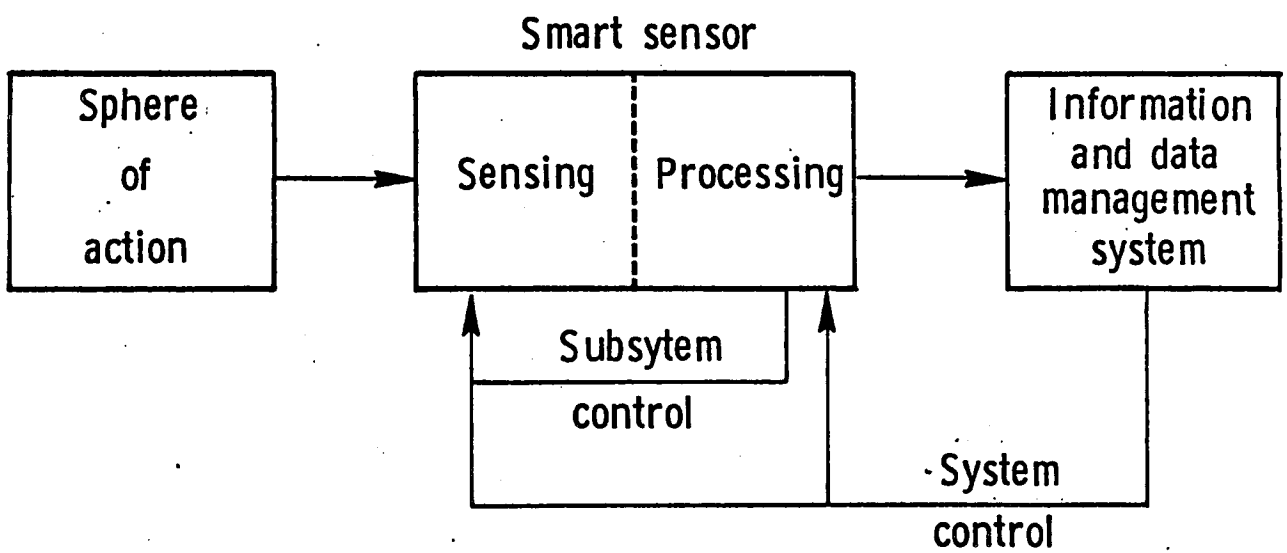
- RENDEZVOUS AND PROXIMITY OPERATIONS HAVE DYNAMIC INFORMATION REQUIREMENTS WHICH PLACE SPECIAL DEMANDS ON SENSORS AND PROCESSORS.
- THE INTEGRATION OF SENSING/PROCESSING REPRESENTS A UNIFIED APPROACH TO MEETING THESE DEMANDS AND IS THE MOST FUNDAMENTAL ASPECT OF SMART SENSORS.
- CURRENT TECHNOLOGY IS DISCUSSED USING EXAMPLES OF SMART SUBSYSTEMS WHICH ADD COMPUTATIONAL CAPABILITY TO A SENSOR.
- ADVANCED CONCEPTS ARE INTRODUCED WHICH COMPLETELY MERGE DATA ACQUISITION AND PROCESSING AT THE DEVICE LEVEL. DETECTOR ARRAY/FOCAL PLANE PROCESSORS ARE PROPOSED AS THE BASIS OF A NEW GENERATION OF MACHINE VISION SYSTEMS.

BASIC INFORMATION PROCESS CYCLE FOR AUTOMATION



SMART SENSOR INFORMATION PROCESSES

- EXPANDED SCHEMATIC

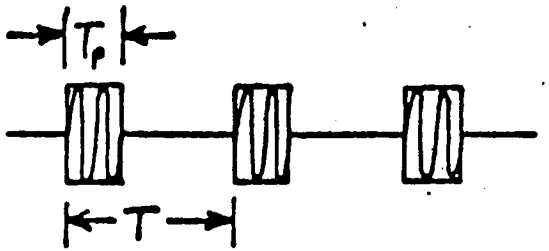


EXAMPLE: LASER RADAR/INTEGRATED PROCESSOR

- MINIATURE SOLID STATE OR DIODE PUMPED ND:YAG LASERS ARE BECOMING AVAILABLE FOR USE FOR SMALL SIZE, REPLACEABLE SUB-SYSTEM PACKAGES.
  - GAAS OR ALGAAS DIODE LASERS ARE AVILABLE WITH SINGLE MODE OPERATION.
  - SMALL PENCIL-LEAD SIZED, DIODE PUMPED ND:YAG LASERS HAVE BEEN DEMONSTRATED.
- LEADING EDGE DISCRIMINATOR ECL-BASED RANGE DETECTOR CIRCUITS HAVE BEEN BUILT THAT CAN DETERMINE PICOSECOND TIME OF FLIGHT RESOLUTION.
- SEVERAL MODULATION TECHNIQUES ARE REQUIRED TO DETERMINE RANGE OR RANGE-RATE.
  - PULSED DOPPLER
  - LONG-PULSE DOPPLER (QUASI-CW)
  - SIMPLE INCOHERENT PULSED FOR RANGE AND RANGE-RATE
  - MULTIPLE TONE MODULATED CARRIER
  - STAGGERED PULSE TRAIN
  - PHASE CODING
  - CHIRP
- THESE CAN BE CONTROLLED BY AN INTEGRATED MICROPROCESSOR WITH INTERNAL DECISION-MAKING TO SELECT THE APPROPRIATE MODULATION TECHNIQUE FOR GIVEN CONDITIONS.
- WITH PROPER HIGH LEVEL INTERFACE TO THE DMS, DIRECT OVERRIDE CAN BE ACCOMPLISHED IN UNIQUE CIRCUMSTANCES.

VU-GRAPH #10

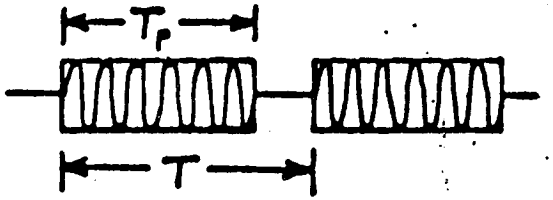
PULSED DOPPLER
(W_x Radar)



$R_{mu} = \frac{cT}{2}$ $V_{mu} = \pm \frac{\lambda}{4T}$

$\Delta R \approx \frac{T_p}{25}$ for smoothed signal; $t_c < \frac{c^2}{8R_m V_m}$

LONG-PULSE DOPPLER
(QUASI-CW)
(Seasat, Het. Lidar)

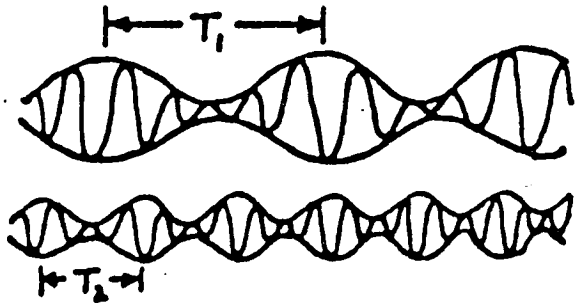


$T_p \gg \frac{1}{f_{D\,MAX}}$ $R_{mu} = \frac{cT}{2}$

RANGE AND RANGE RATE
(Incoherent Carrier)

$R_{mu} = \frac{cT}{2}$ $V = \frac{\Delta R}{\Delta t}$

MULTIPLE TONE
MODULATED CARRIER
(LM rendezvous radar
surveying insts.)

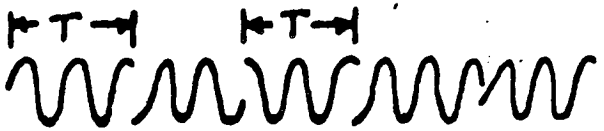


$\Delta R \approx \frac{cT_2}{4000}$ (β - multiplication method; VALT program)

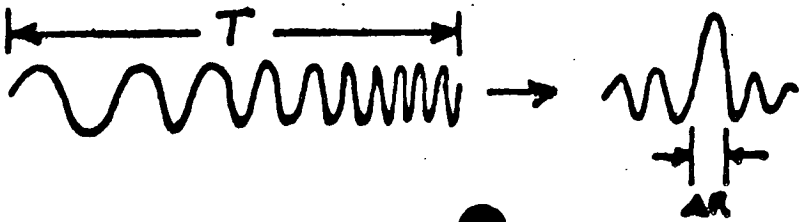
STAGGERED PULSE TRAIN

Lowered and broadened Ambiguity Function side-lobes

PHASE CODING

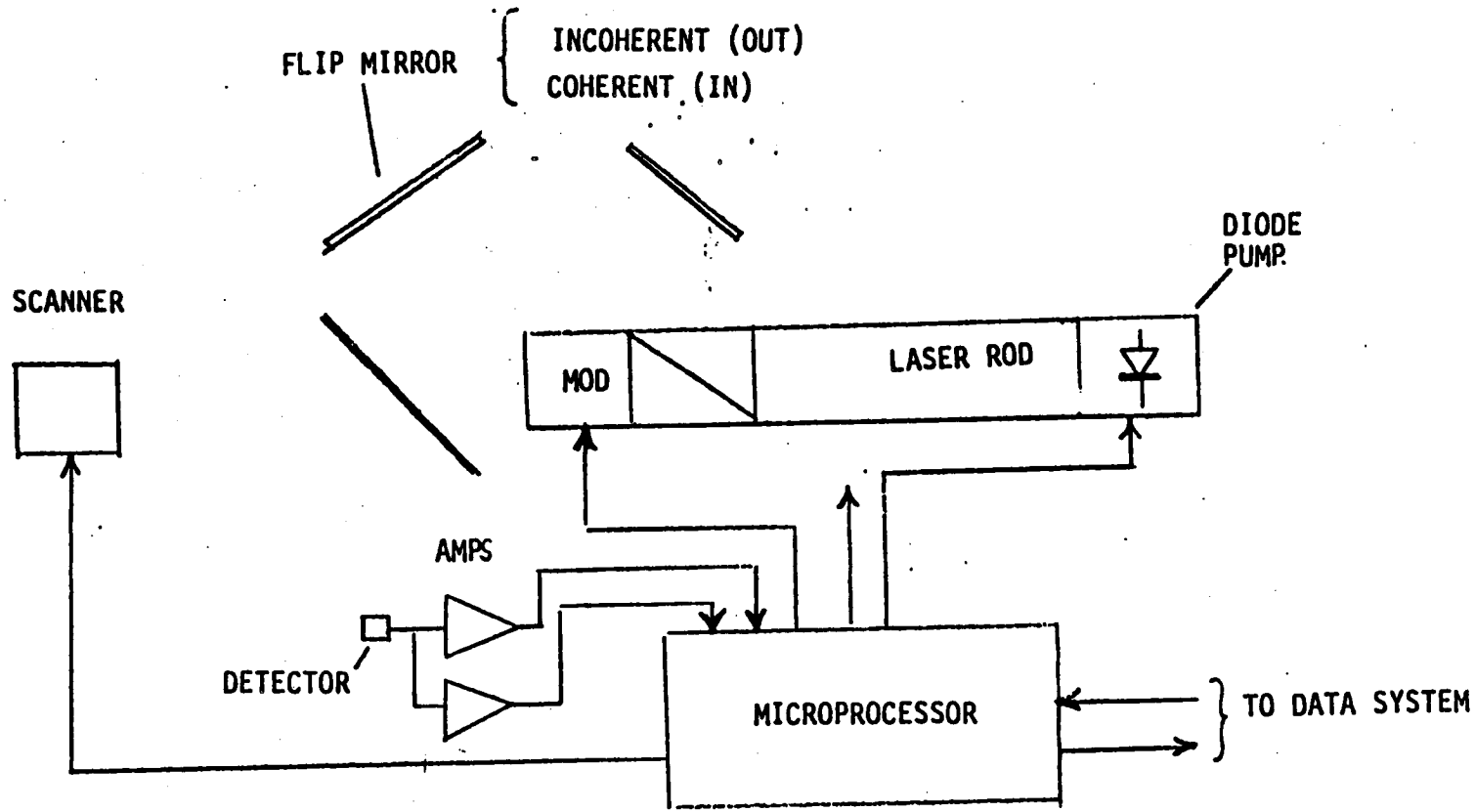


CHIRP



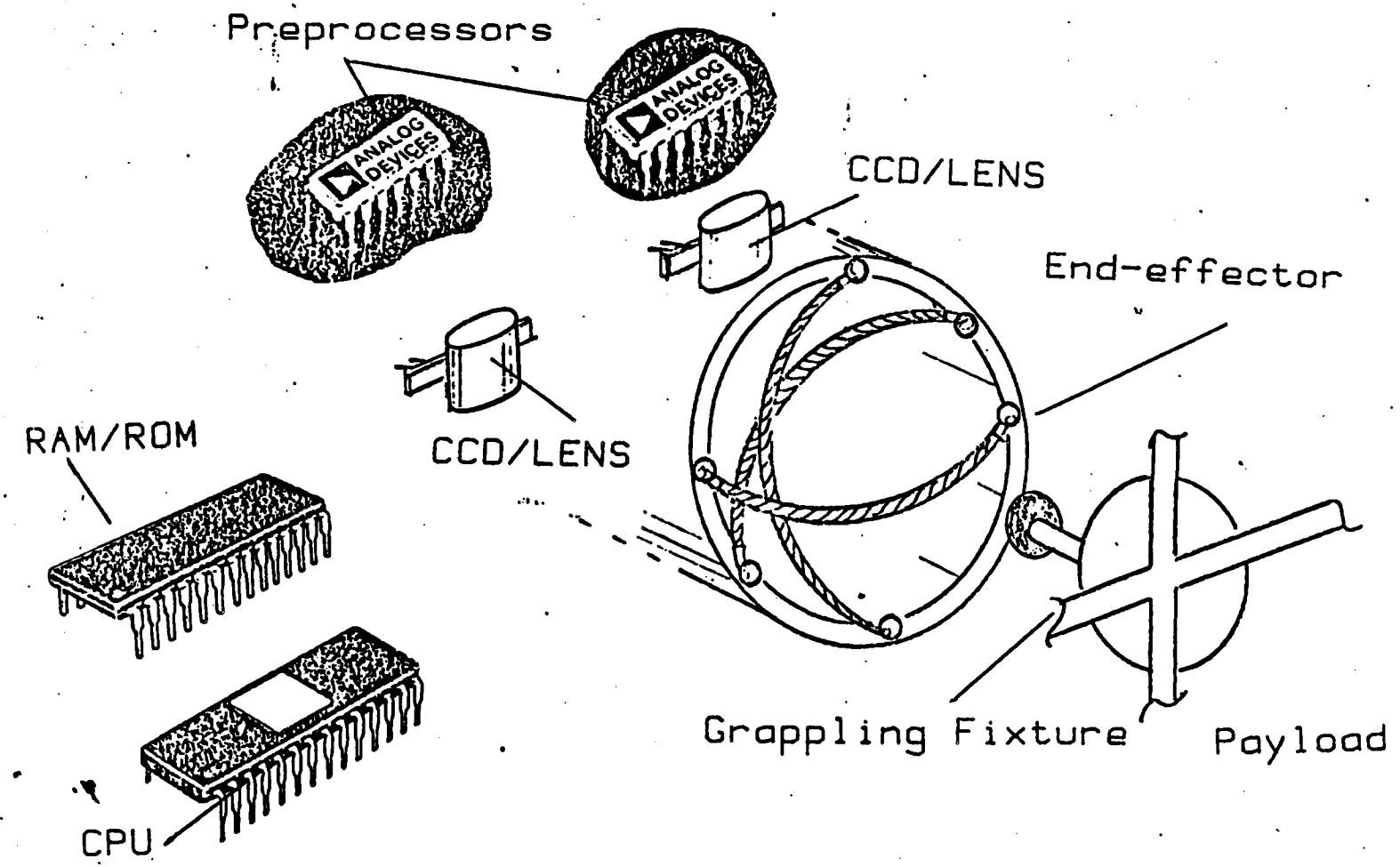
Resolution of short pulse; peak power of long pulse

MINIATURE LASER RADAR SCHEMATIC



NASA

THE SMART END-EFFECTOR



To RMS Control System

10-148

ORIGINAL FOR

Page 10-149

NOT AVAILABLE

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NASA

MANIPULATOR DEVELOPMENT FACILITY

* THE MDF IS ONE OF THE GROUND TRAINERS USED BY THE ASTRONAUTS TO GAIN EXPERIENCE WITH THE REMOTE MANIPULATOR SYSTEM

* THE MDF IS DESIGNED TO REASONABLY WELL SIMULATE THE RMS IN END EFFECTORS FORCES AS WELL AS TIP SPEEDS

* THE MDF HAS BEEN USED TO, AMONG OTHER THINGS, ESTIMATE BERTHING AND RELEASE TIMES FOR SUCH SIMULATED PAYLOADS AS:

  IECM - INDUCED ENVIRONMNETAL CONTAMINATION MODULE
  PDP - PLASMA DIAGNOSTICS PACKAGE
  SPAS - SHUTTLE PALLET SATELLITE
  LDEF - LONG DURATION EXPERIMENT FACILITY

* RESULTS, COMPLETE WITH TEST SUBJECT RUN TIMES AND DETAILED TEST PROCEDURES ARE ROUTINELY DONE AT JSC AND ARE AVAILABLE VIA DISTRIBUTION

MANUAL VS. AUTOMATED RMS

PROGRAM	ACTUAL TEST (SECONDS)	AUTOMATED (SECONDS)	IMPROVEMENT FACTOR
PDP	406.2	42.2	9.6
OCP	1087	255.6	4.3
LDEF	2351	200.6	11.7
IECM	386	36.2	10.7
SPAS-01	366	27.8	13.2

AVERAGE IMPROVEMENT FACTOR = 9.9

HRK 2/18/85

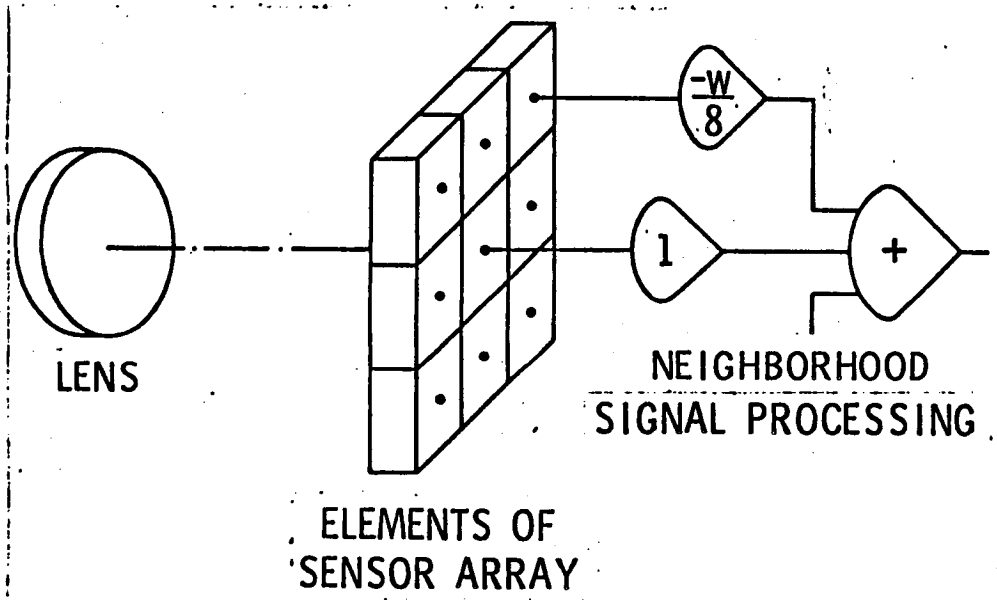
DETECTOR ARRAY/FOCAL PLANE PROCESSING CONCEPTS FOR MACHINE VISION

- A MAJOR CHALLENGE FOR MACHINE VISION IS THE CONVERSION OF INTENSITY VALUES IN THE OPTICAL IMAGE INTO SCENE STRUCTURAL INFORMATION.
- A PRINCIPAL OBSTACLE IS THE SHEER BULK OF DATA IN AN OPTICAL IMAGE.
- DETECTOR ARRAY/FOCAL PLANE PROCESSING CONCEPTS OFFER A NEW APPROACH TO MACHINE VISION.
  - INCORPORATES IMAGING OPTICS DESIGN INTO PROCESSING.
  - RELIEVES LOW LEVEL IMAGING PROCESSING BURDEN PLACED ON CPU.
  - STREAMLINES OVERALL ARCHITECTURE BY ACCOMPLISHING EDGE ENHANCEMENT AND DATA COMPRESSION IN SENSOR FRONT END.
  - CAN BE MODIFIED TO ADD MOTION DETECTION.

FOCAL-PLANE PROCESSING OF VISUAL INFORMATION

CONCEPT: EDGE DETECTION

APPROACH



COMBINE OPTICAL FILTERING WITH FOCAL-PLANE PROCESSING TO SHAPE SPATIAL RESPONSE OF SENSOR-ARRAY IMAGING SYSTEM

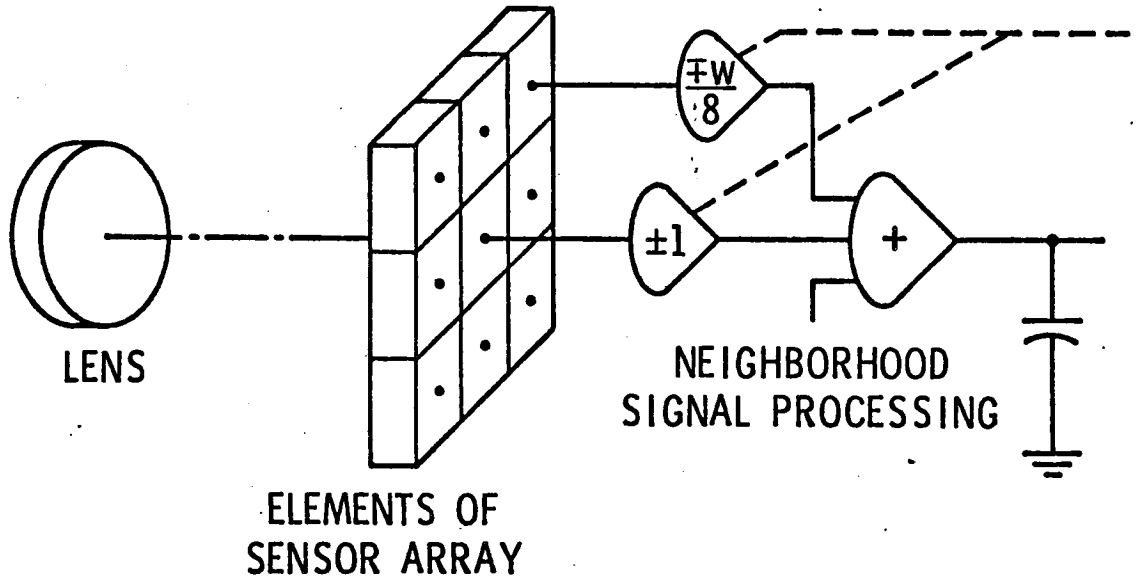
ADVANTAGES

- REDUCED SIGNAL PROCESSING
- REDUCED DATA TRANSMISSION
- IMPROVED EDGE ENHANCEMENT

} EFFICIENT EXTRACTION OF ESSENTIAL VISUAL INFORMATION FOR SUBSEQUENT PATTERN RECOGNITION

FOCAL-PLANE PROCESSING OF VISUAL INFORMATION

CONCEPT: MOTION DETECTION AND TRACKING



SIGN REVERSAL OF WEIGHTING PARAMETERS CAUSES SUCCESSIVE IMAGES TO BE SUBTRACTED, THUS ISOLATING DIRECTION AND RATE OF ANY MOTION

SUMMARY AND RECOMMENDATIONS

- INTEGRATED SENSING/PROCESSING WAS PRESENTED AS AN ELEMENT OF SMART SENSORS AND RELATED TO INFORMATION ACQUISITION WHICH IS ESPECIALLY IMPORTANT TO EFFICIENT RENDEZVOUS AND PROXIMITY OPERATIONS.

- CURRENT TECHNOLOGIES ARE AVAILABLE FOR CONSIDERATION AS THE BASIS FOR ADVANCED INSTRUMENTATION AIMED TOWARD IMPROVING HUMAN EFFICIENCIES IN SPACE OPERATIONS.

- STUDIES SHOULD BE PERFORMED TO SELECT THE MOST PROMISING INSTRUMENTATION TECHNOLOGIES FOR APPLICATION TO CRITICAL SPACE OPERATIONS.

- LABORATORY AND FLIGHT DEMONSTRATIONS OF ADVANCED INSTRUMENTATION FOR RENDEZVOUS AND PROXIMITY OPERATIONS ARE NECESSARY TO BUILD THE PROPER LEVEL OF CONFIDENCE TO ENSURE THEIR APPLICATION TO THE SPACE TRANSPORTATION SYSTEM.

ADVANCED SEMICONDUTOR/SOLID STATE LASER SOURCES FOR RANGING AND ILLUMINATION

DONALD B. CARLIN
RCA LABORATORIES
PRINCETON, NJ 08540

251-01

FIGURE 1

A typical, gain-guided AlGaAs double-heterojunction diode laser is shown. The current distribution, and therefore the gain region, in this type of device is determined by a stripe etched through a SiO_2 insulating layer, upon which a broad area metallic contact is deposited. Of particular importance is the optical output radiation pattern emerging from the emitting facet. This is a diverging beam of elliptical cross-section. Typically, the extent of the beam in the transverse direction (perpendicular to the heterojunction plane) is two to five times that of the lateral direction (parallel to the junction plane).

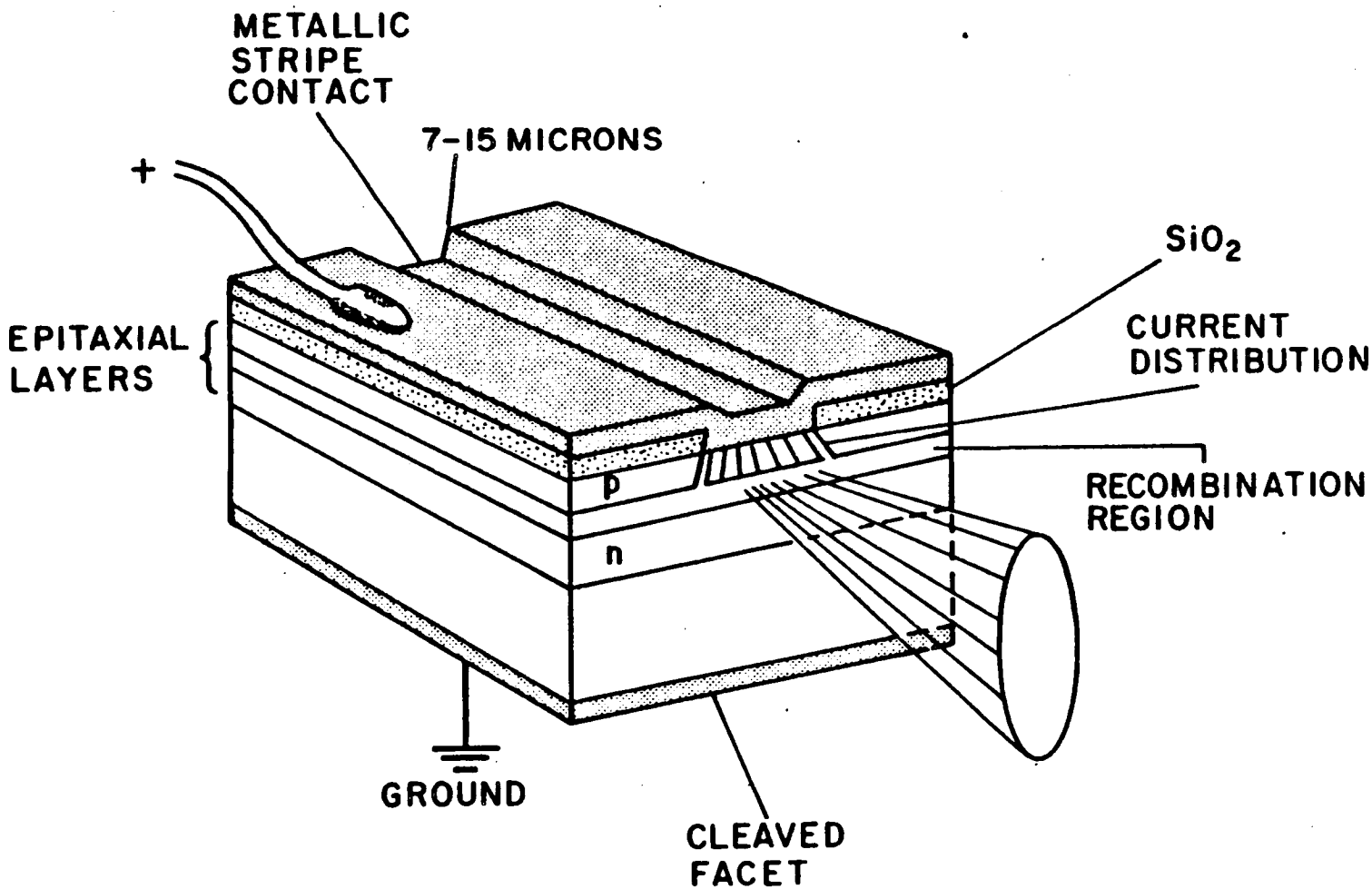

METALLIC
STRIPE
CONTACT
7-15 MICRONS
+
EPITAXIAL
LAYERS
SiO_2
CURRENT
DISTRIBUTION
RECOMBINATION
REGION
p
n
GROUND
CLEAVED
FACET

Figure 1

FIGURE 2

RCA is developing high-power diode lasers for use in optical communications and recording systems. Any astigmatism in the diode laser will manifest itself in either the collimated beam in free-space communications systems or in the focal region of optical recorders. In gain-guided devices, the optical mode in the lateral direction is determined by the injection current distribution, and therefore changes with drive current. An optical waveguide, formed by $Al_xGa_{1-x}As$ layers, strongly confines the optical mode in the transverse direction. In this direction, the mode will always have an apparent source at a constant distance within the laser. In the lateral direction, the apparent source moves depending on drive current, and creates a varying astigmatism of ~20 μm. Fixed-value optics can collimate such a beam in only one direction, as shown in the figure.

RCA

Astigmatism in Gain-Guided Diode Lasers

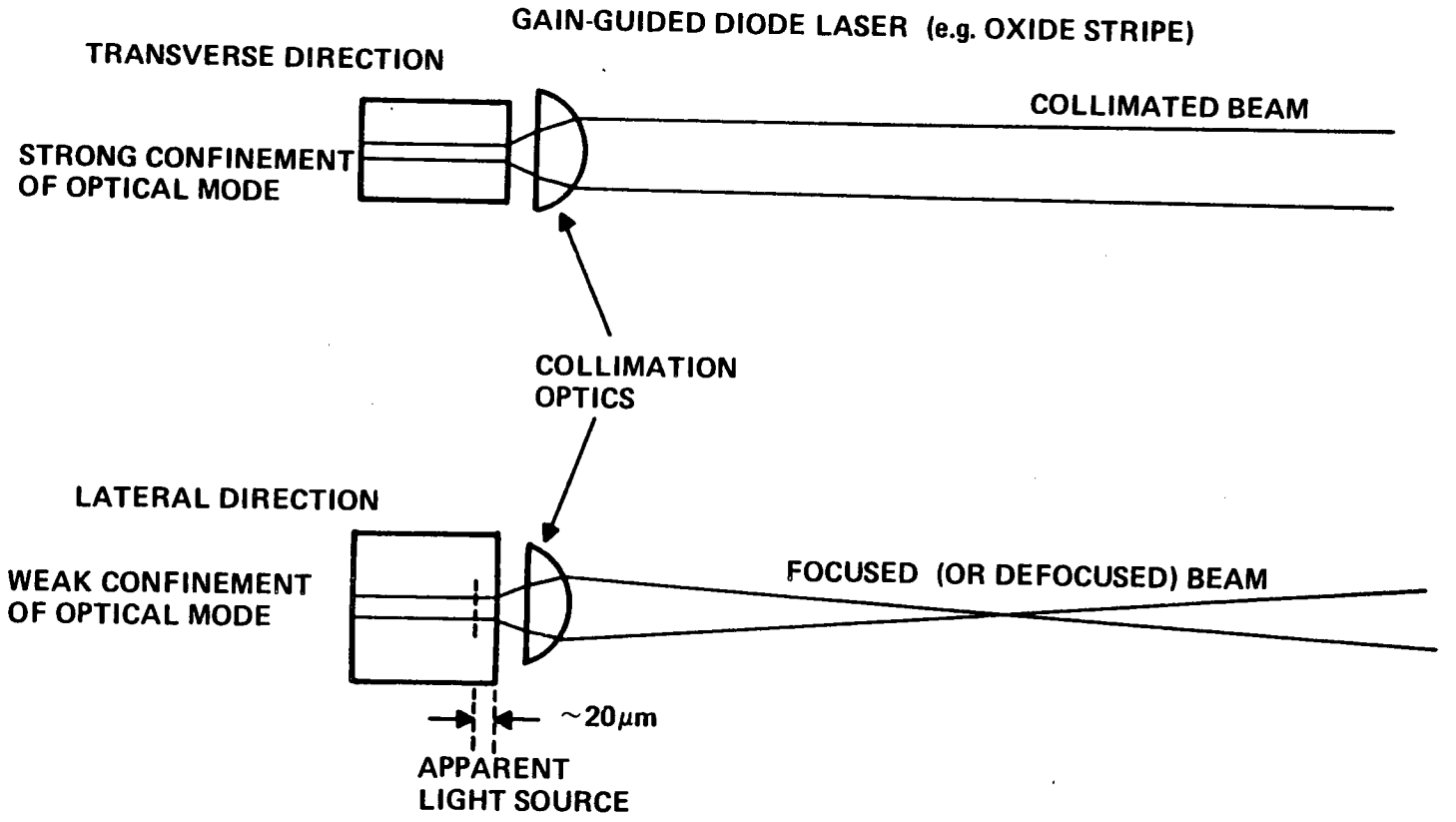


Figure 2

10-160

FIGURE 3

Index-guided devices, such as the buried heterojunction (BH), channeled-substrate-planar (CSP), or constricted-double-heterojunction large-optical-cavity (CDH-LOC) have optical modes which are strongly confined in both the lateral and transverse directions by refractive index variations and have negligible astigmatism. The output beam can therefore be collimated in both directions.

RCA

Anastigmatic Index-Guided Diode Lasers

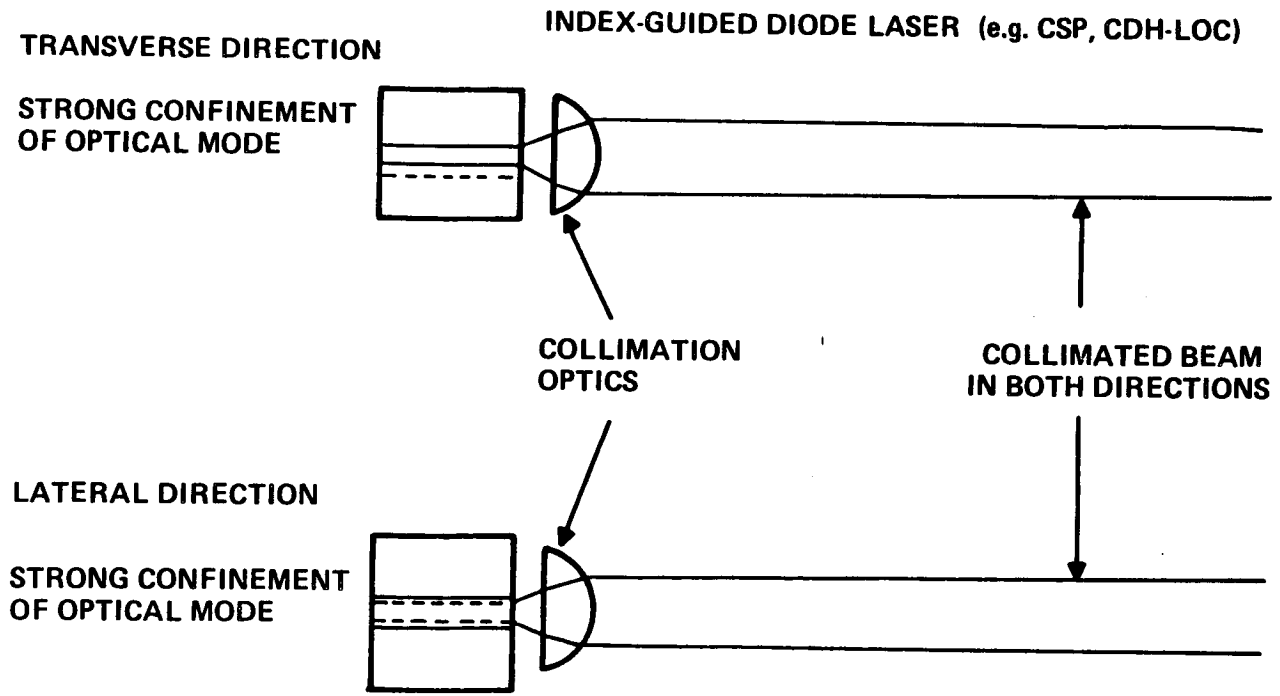


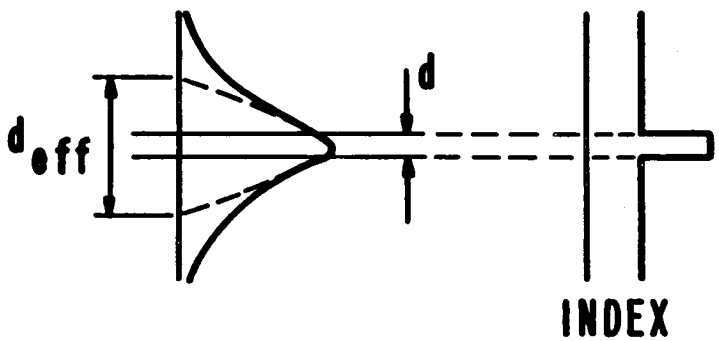
Figure 3

FIGURE 4

Facet degradation is a primary limitation on the output power attainable from a diode laser. Increased spot area allows reduced photon flux, and therefore reduced probability for facet damage. Two methods of increasing the dimension of the spot in the transverse direction are shown. On the left is a thin-active (TA) double-heterojunction, typified by CDH and CSP structures. Solution of the wave equation in this type of waveguide shows an inverse relationship between effective spot size and active layer thickness. A large-optical-cavity structure, typified by the CDH-LOC, is shown on the right. The effective spot width is primarily determined by the thickness (D) of the LOC layer. The maximum transverse spot sizes achieved in LOC structures exceeds those in TA lasers, thus the former can, in principal, be made more powerful than the latter.

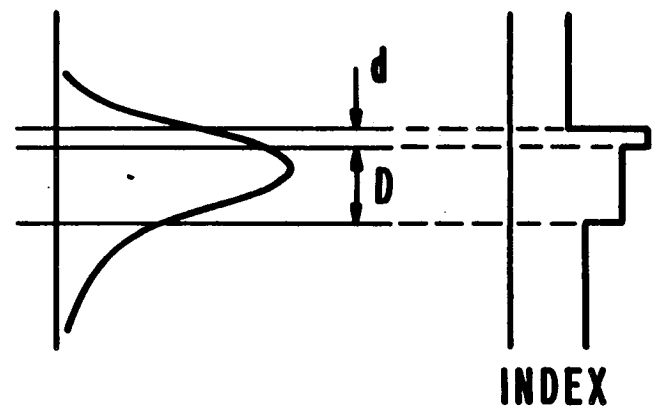
TRANSVERSE SPOT SIZE

THIN-ACTIVE (TA)
DH STRUCTURE



d	d_{eff}
0.05 μm	1.00 μm
0.15 μm	0.60 μm

LARGE-OPTICAL-CAVITY (LOC)
STRUCTURE



$$\left.\begin{array}{l} d \simeq 0.1\,\mu m \\ D = 1.0 - 2.0\,\mu m \end{array}\right\} d_{eff} = 1.5 - 2.0\,\mu m$$

Figure 4

10-164

FIGURE 5

A schematic drawing of a current-confined CDH-LOC diode laser is shown. This structure is grown over the mesa between two dovetail-shaped channels etched in a GaAs substrate and has typical layer compositions as shown. The optical spot size at the facet is typically 5.5 x 1.7 μm full-width at $1/e^2$ of the peak intensity. This device is an improvement over the standard CDH-LOC in that the current distribution is more tightly confined by diffusion of zinc through the cap layer, increasing the electrical-to-optical power conversion efficiency.

CURRENT-CONFINED CDH-LOC LASER

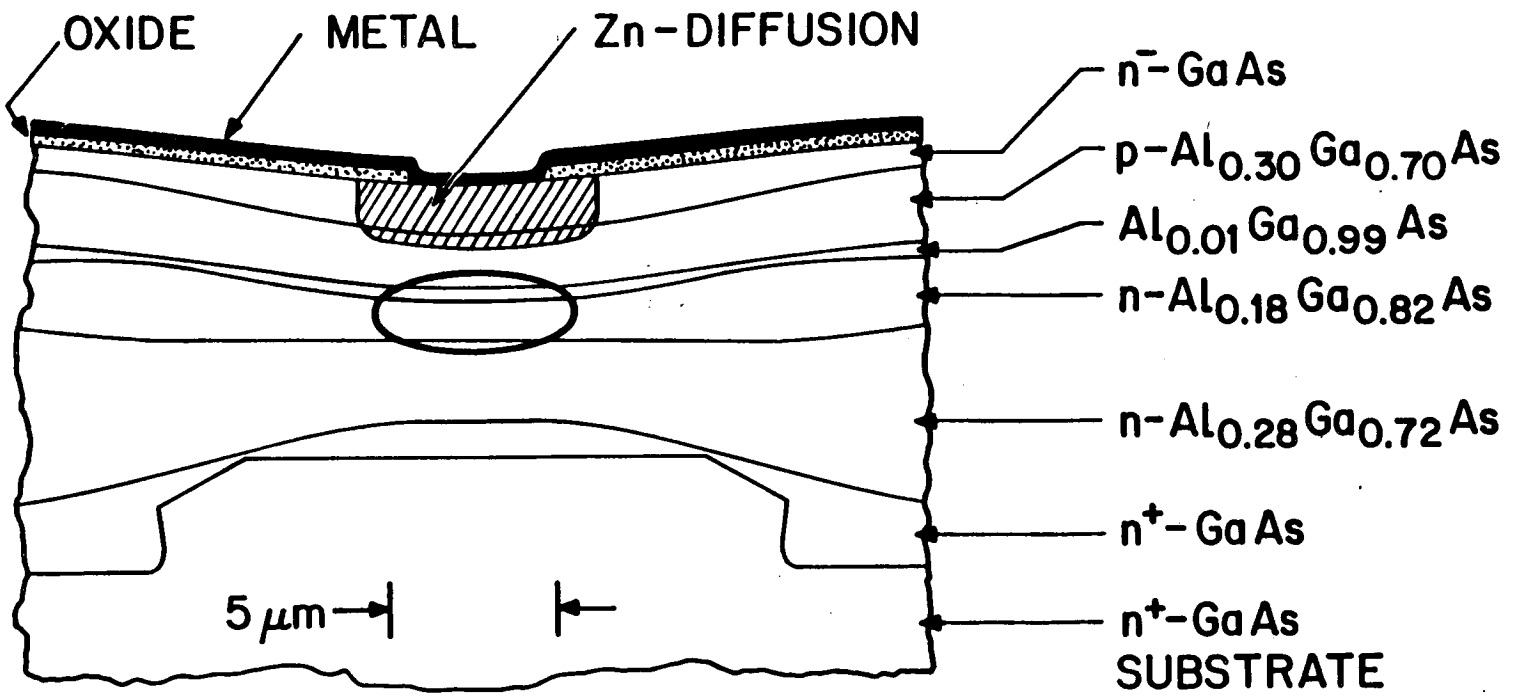


Figure 5

FIGURE 6

A current-confined CDH-LOC laser achieved 165 mW output from one emitting facet, with an exceptionally high power conversion efficiency which approaches 35%.

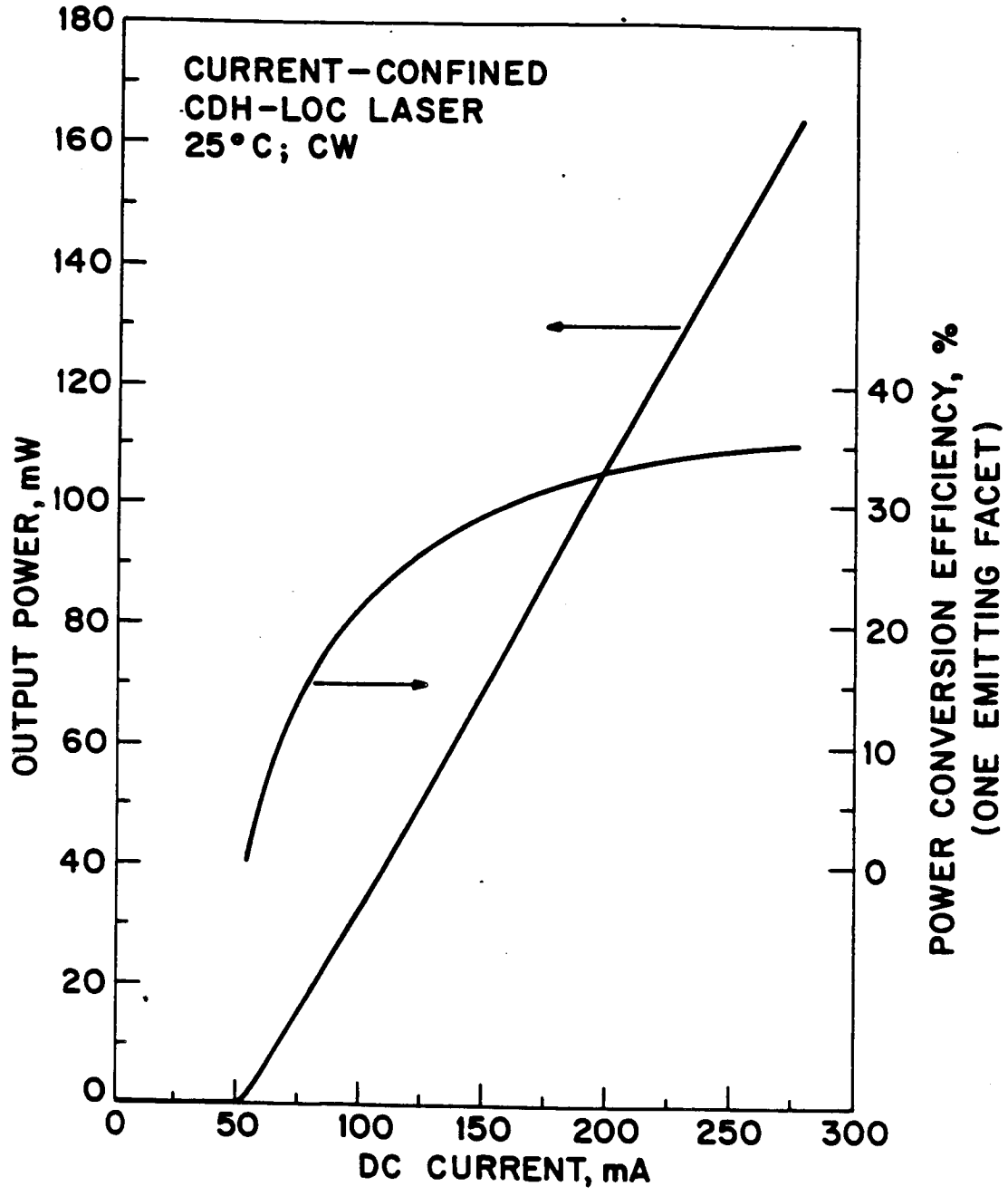

CURRENT-CONFINED
CDH-LOC LASER
25°C; CW
OUTPUT POWER, mW
POWER CONVERSION EFFICIENCY, %
(ONE EMITTING FACET)
DC CURRENT, mA
0
20
40
60
80
100
120
140
160
180
0
10
20
30
40
0
50
100
150
200
250
300

Figure 6

FIGURE 7

This CDH-LOC device achieved 40 mW cw in a single spectral and spatial mode, and 60 mW cw in a single spatial mode.

VK-25-11

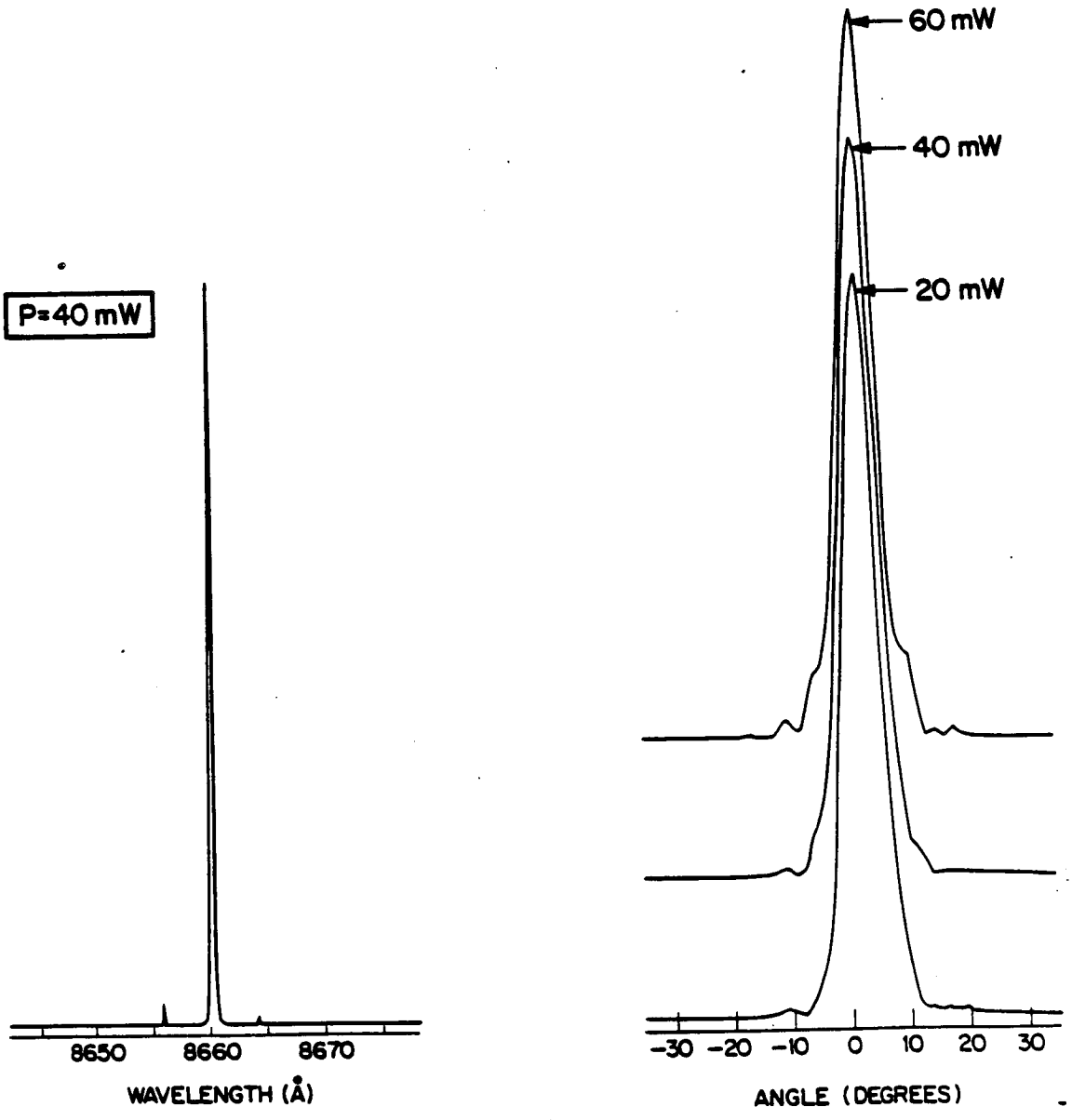


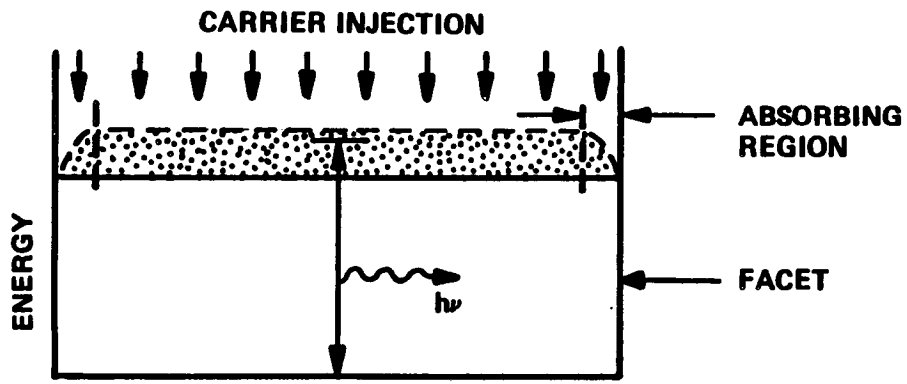
Figure 7

FIGURE 8

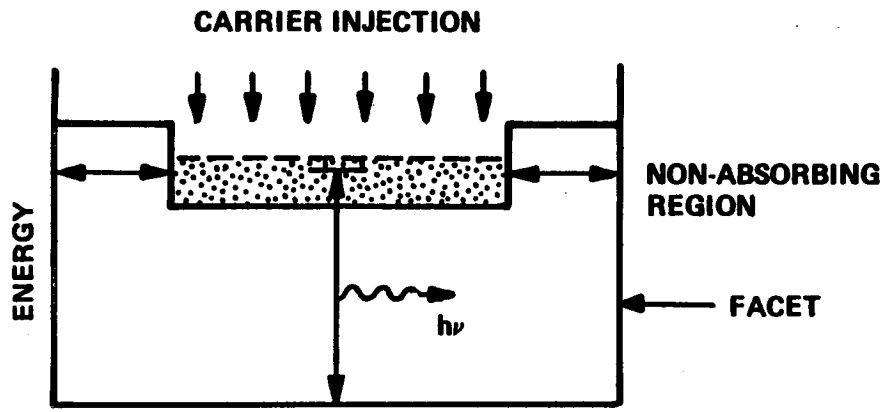
A potential method for increasing the output power of diode lasers is the reduction of facet damage induced by photon absorption. The lasing light is absorbed by surface states in the regions near the facets, which lie within the bandgap of the material. This absorption causes heating and eventual catastrophic facet damage due to melting. Such absorption can be eliminated by growing higher bandgap material near the facets, so that the lasing photons do not have sufficient energy to populate the surface states.

NON-ABSORBING-MIRROR (NAM) LASER STRUCTURES

CONVENTIONAL LASER



NAM LASER



MEANS OF ACHIEVING NAM LASERS:

- PREFERENTIAL DEEP Zn-DIFFUSION
- BURIED-FACET

Figure 8

10-172

FIGURE 9

Shown is a non-absorbing-mirror (NAM) structure applied to a CDH-LOC device. The 20 to 30% Al concentration of the AlGaAs material in the facet regions has a sufficiently higher bandgap than exists in the $Al_{.05}Ga_{.95}As$ active region so that the surface states cannot be populated and the lasing light will not be absorbed.

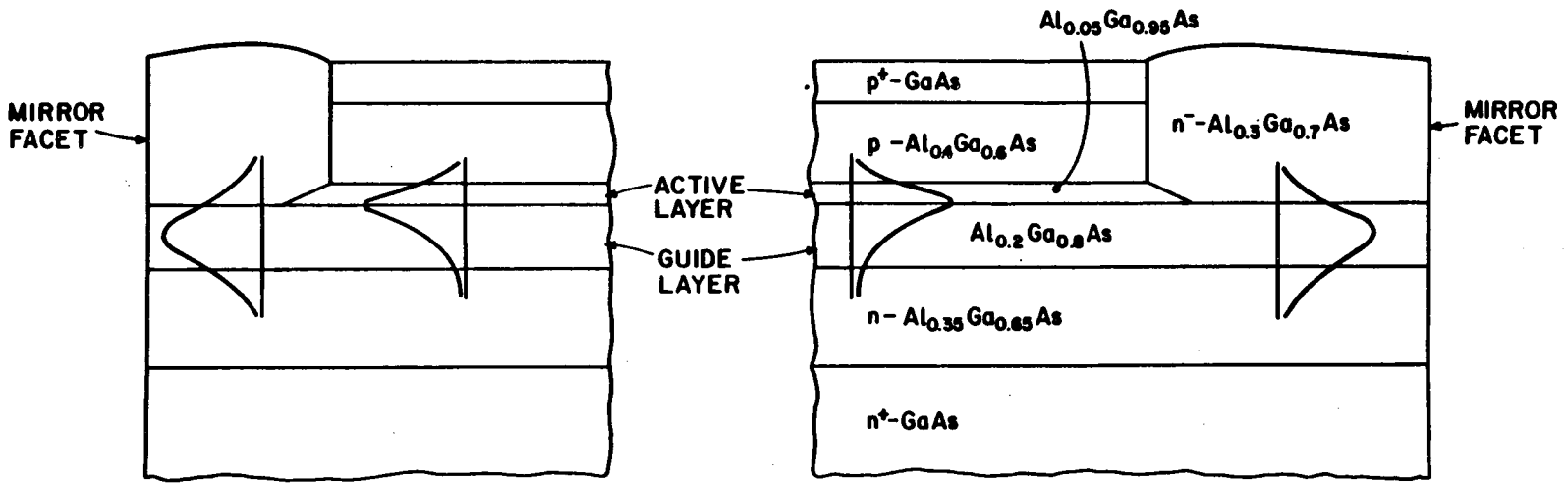

MIRROR FACET
ACTIVE LAYER
GUIDE LAYER
$Al_{0.05}Ga_{0.95}As$
p^+-GaAs
p -$Al_{0.4}Ga_{0.6}As$
n^--$Al_{0.3}Ga_{0.7}As$
$Al_{0.2}Ga_{0.8}As$
n- $Al_{0.35}Ga_{0.65}As$
n^+-GaAs
MIRROR FACET

Figure 9

FIGURE 10

The optical power output-versus-drive current characteristics of a prototype NAM-CDH-LOC is plotted, as is that of the most powerful CDH-LOC devised without a NAM region. A four-fold increase in output power was observed.

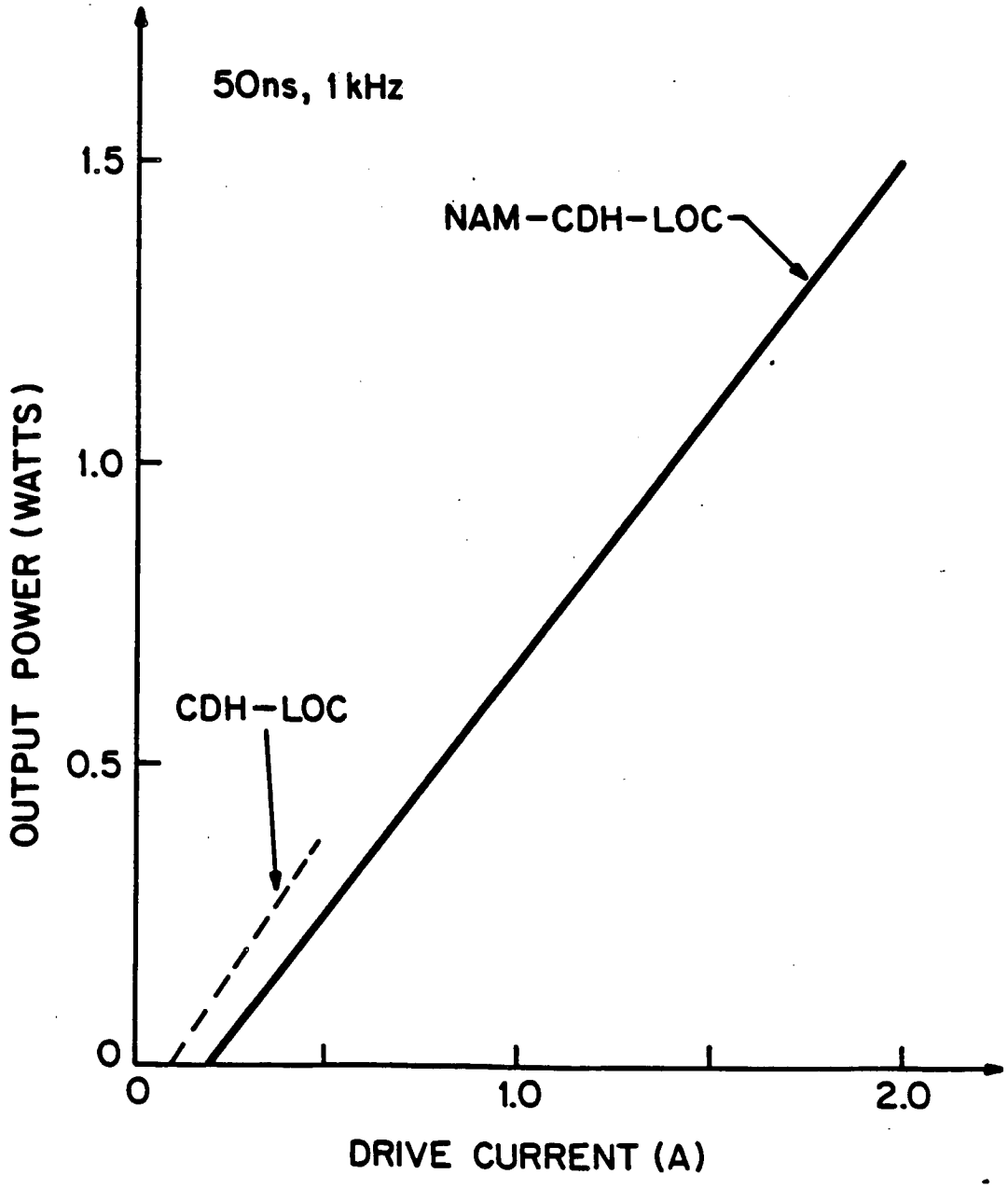
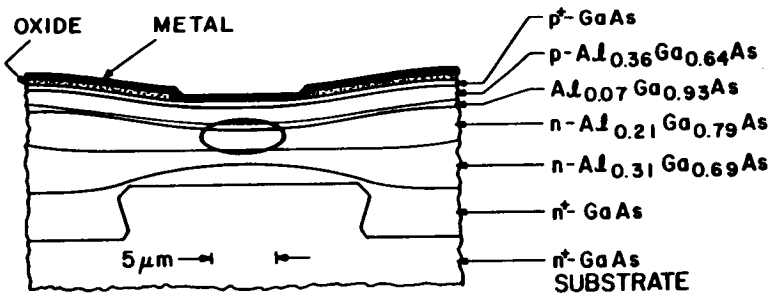

50ns, 1 kHz
1.5
1.0
0.5
0
OUTPUT POWER (WATTS)
NAM-CDH-LOC
CDH-LOC
0
1.0
2.0
DRIVE CURRENT (A)

Figure 10

FIGURE 11

This figure shows the structures of both the CDH-LOC and CSP (channeled-substrate-planar) devices. Although the spot size at the facet of the CDH-LOC is larger than that of the CSP, both achieve comparable output powers in production.

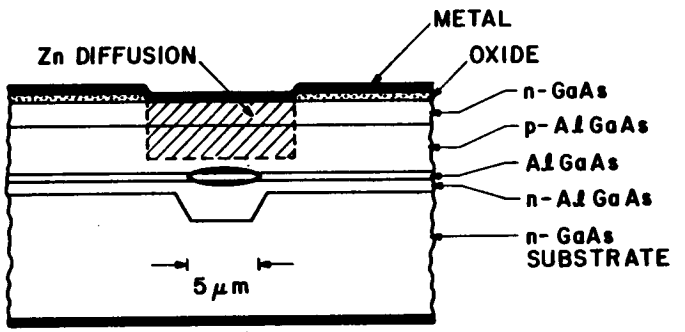
CDH-LOC



- Lateral antiguiding
- I_{th} = 60-100 mA
- Spot size: 5.0 μm x 1.5 μm
- $\theta_{\parallel} \times \theta_{\perp}$ = 6° x 25°
- Max single-mode

  cw power: 50 mW
  (TH-LOC)

CSP



- Lateral absorption
- I_{th} = 60-100 mA
- Spot size: 3.5 μm x 1.0 μm
- $\theta_{\parallel} \times \theta_{\perp}$ = 10° x 27°
- Max single-mode

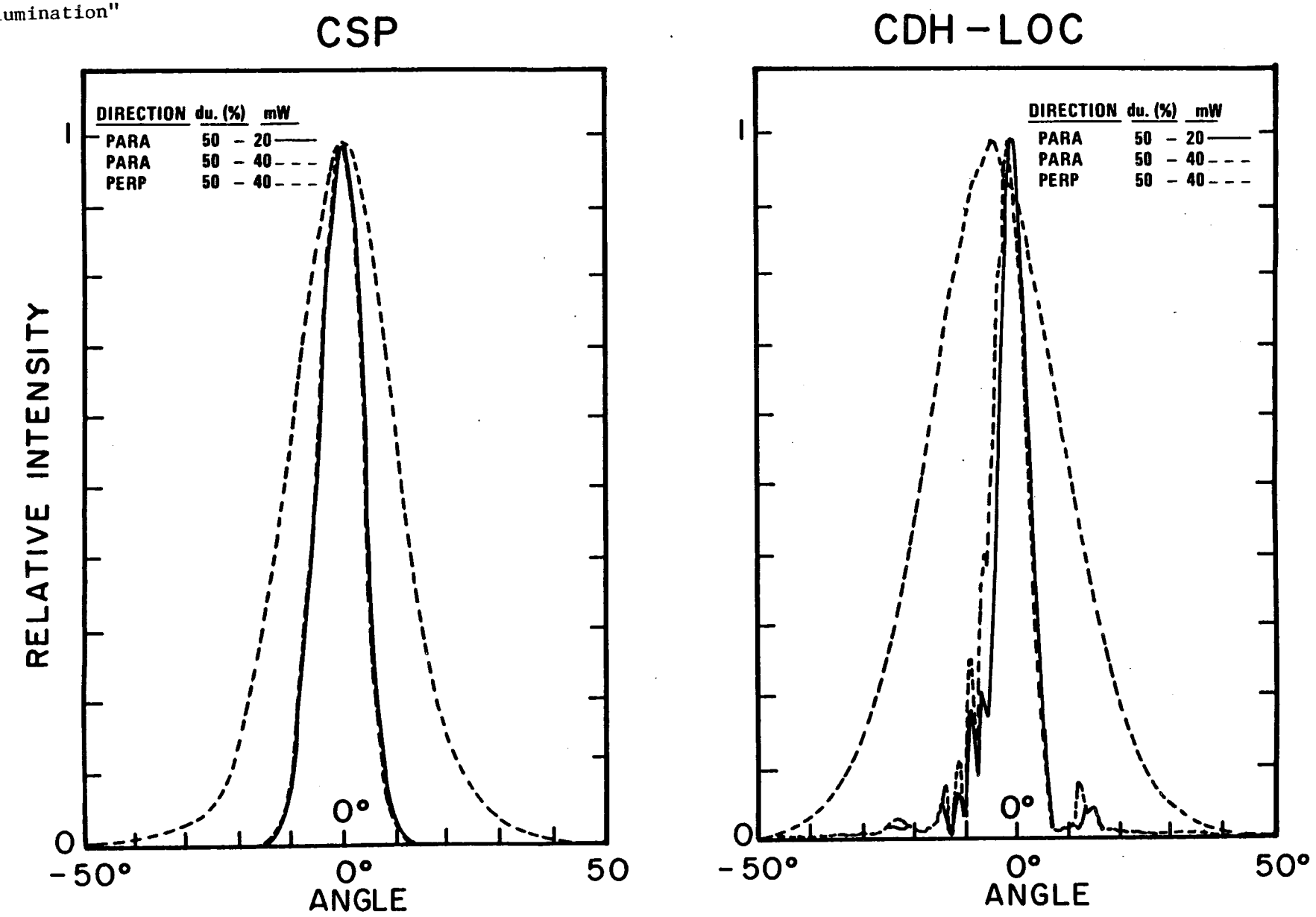
  cw power: 50 mW
  (TRS)

Figure 11

10-178

FIGURE 12

Shown are far-field patterns of RCA-developed CSP and CDH-LOC lasers. The CDH-LOC far-field, while narrower than that of the CSP, is often characterized by side-lobes and non-uniformities generated by the leaky antiguiding nature of the device. The patterns often shift direction slightly because the lateral index-guide is relatively weak. The CSP far-fields show less of these characteristics due to the strong absorption of the laser light outside the channel region of the structure.



FAR-FIELD INTENSITY PROFILES

Figure 12

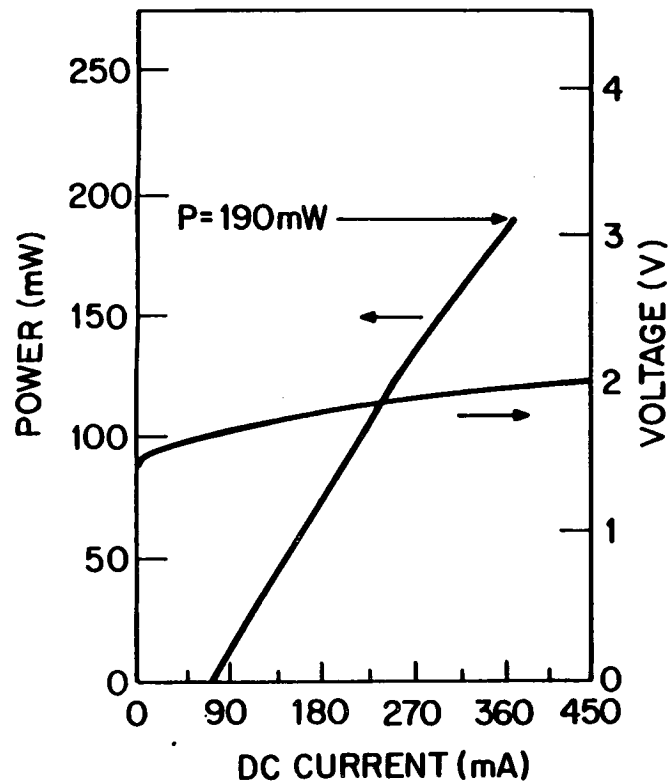
081-01

FIGURE 13

Results are shown for a CSP laser recently grown at RCA Laboratories. The device achieved 190 mW cw total output and 150 mW cw in a single spatial mode.

RCA Laboratories

CSP DIODE LASER



CSP CROSS-SECTION

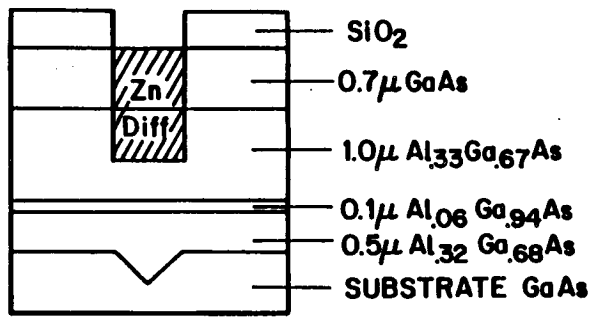


Figure 13

10-182

FIGURE 14

Power-versus-current, spectra and far-field intensity profiles are shown at four cw power levels from 50 mW to 150 mW for this CSP device. The spectra show a single spectral mode to almost 90 mW cw and a single, fundamental spatial mode to 150 mW cw.

RCA Laboratories

CSP DIODE LASER

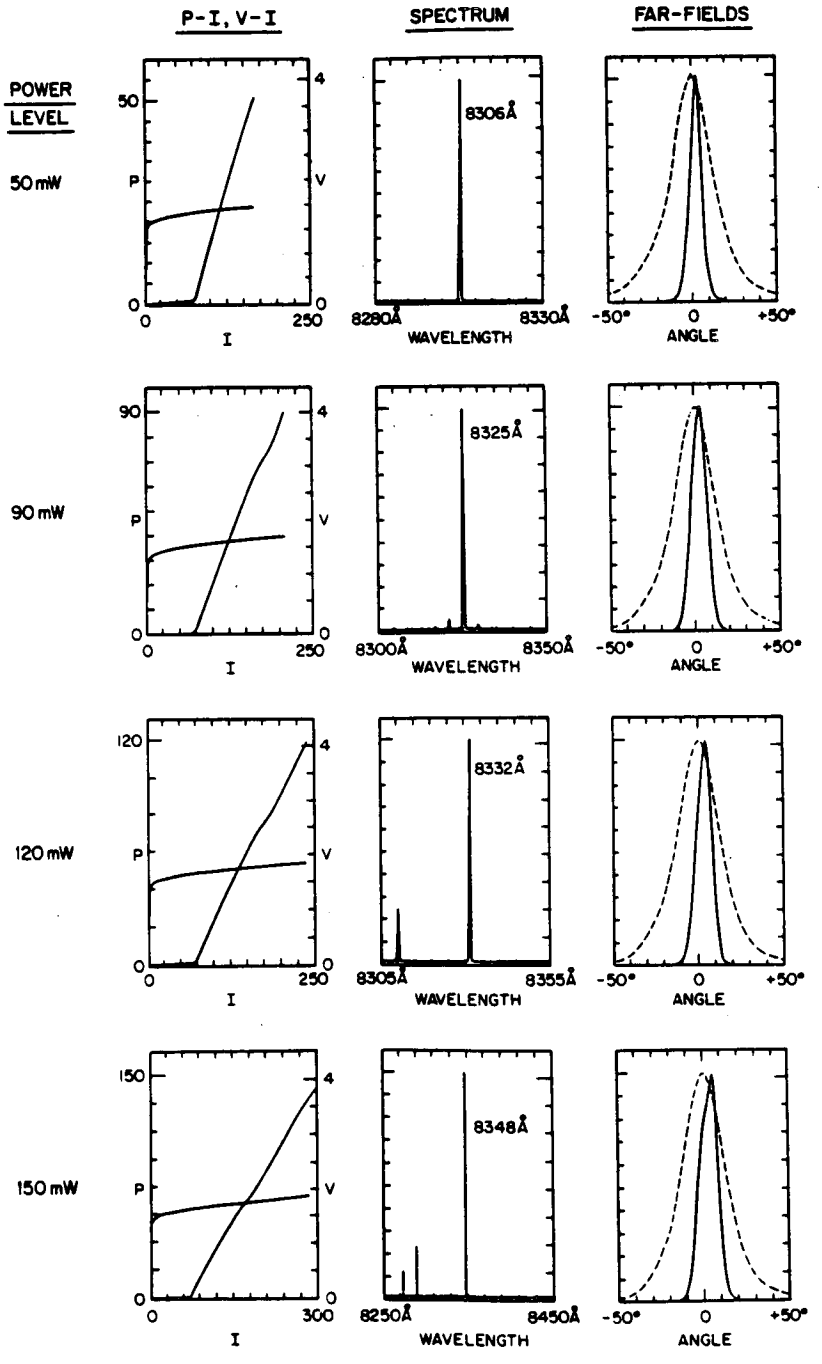


Figure 14

10-184

FIGURE 15

Life test data are shown for seven CSP diodes operating at 20 mW cw and 30°C. Constant output power is made by current variation. None of the diodes have shown an appreciable increase in drive current after 3,000 hours of continuous operation.

CSP LASER DIODE AGING TIME AT 30 DEGREES

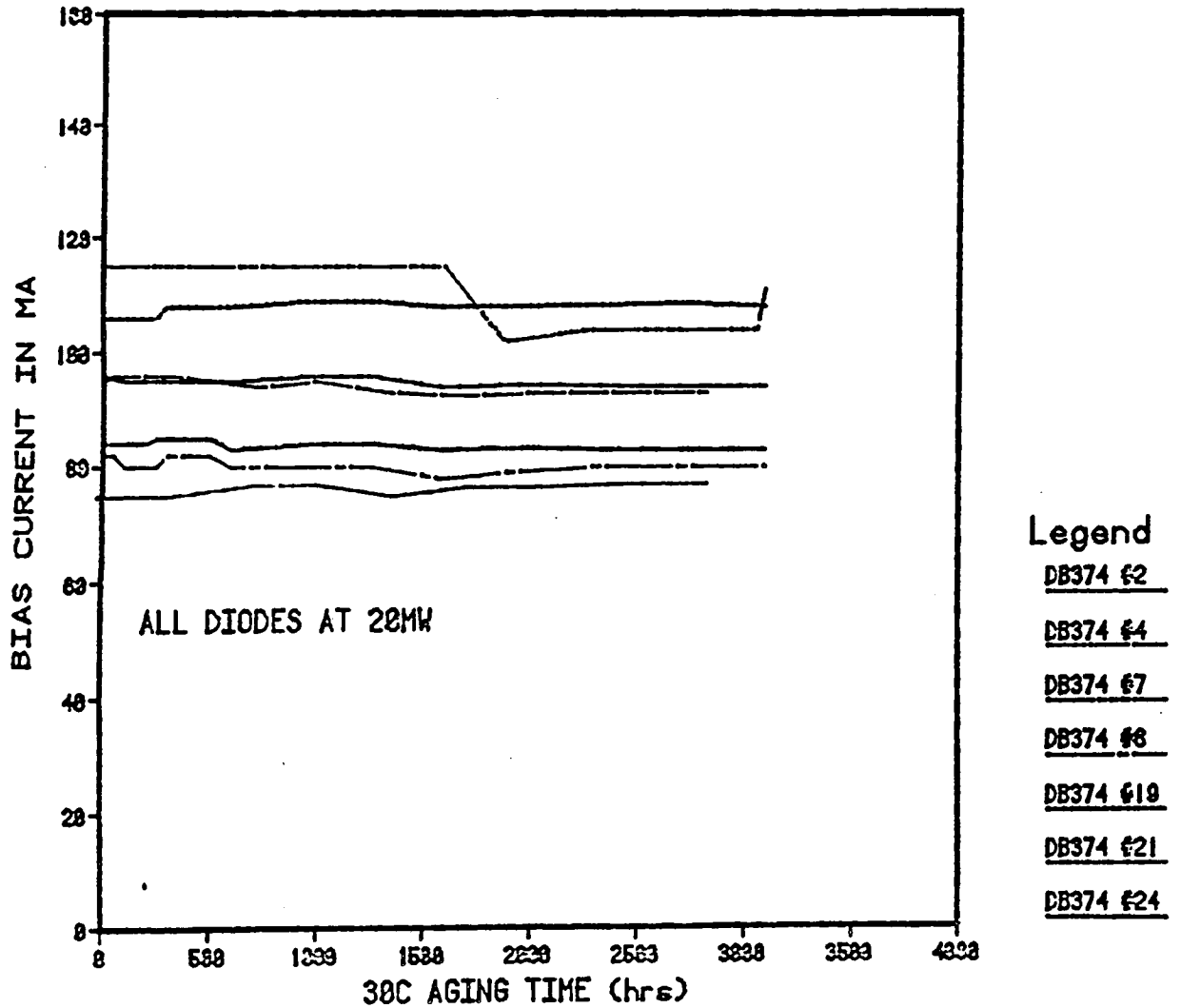


Figure 1

FIGURE 16

A comparison of the power-versus-current characteristics of the most powerful AlGaAs diode lasers published to date are shown in this figure. The company which developed each device, along with the name and device type, are indicated.

RCA Laboratories

INDUSTRY COMPARISON OF DIODE LASERS

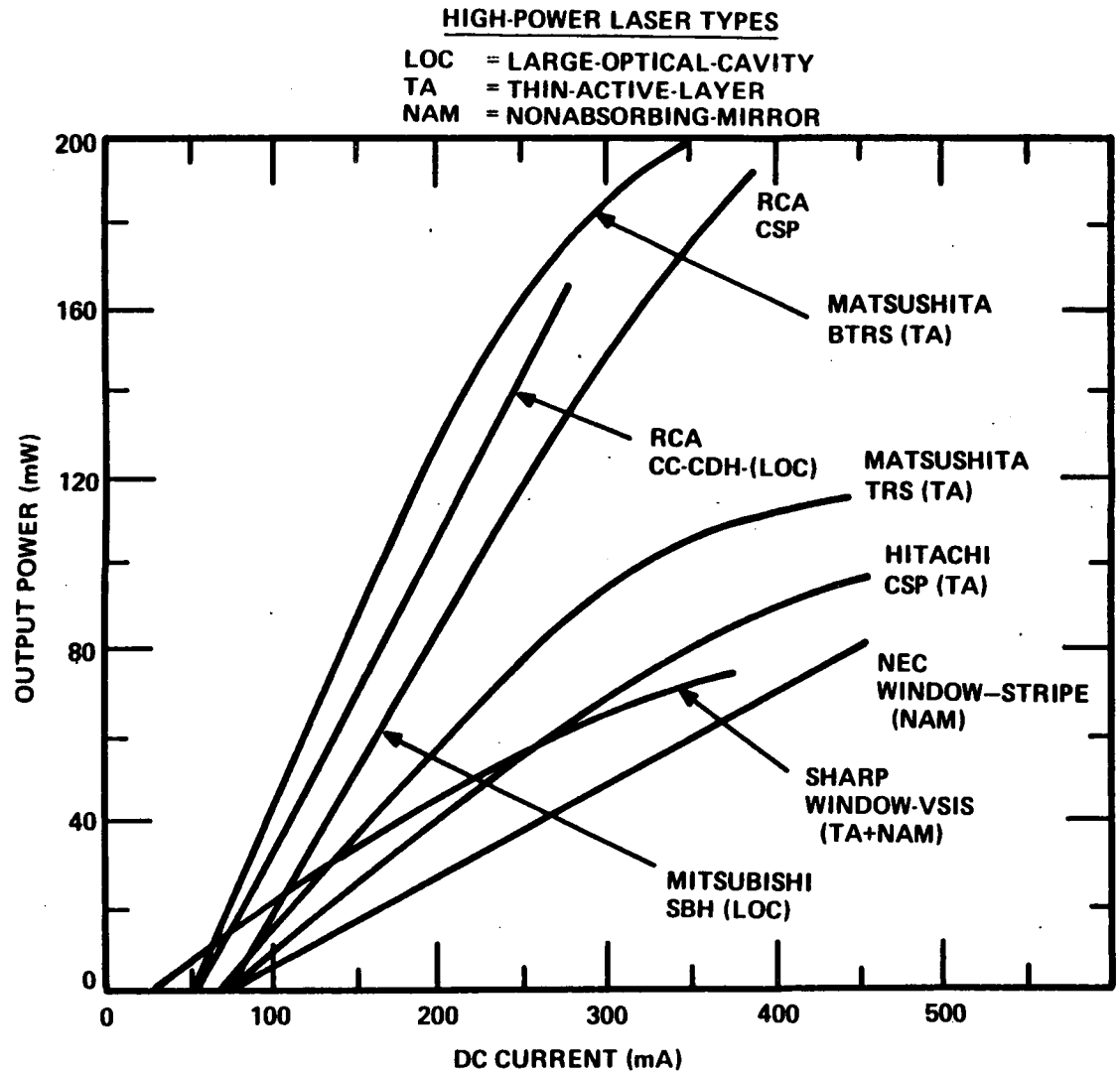


Figure 1

10-188

FIGURE 17

This figure shows the near-field amplitudes and corresponding far-field intensity profiles from phase locked arrays of closely coupled diode lasers. The upper figures depict the desired situation, i.e., the electric fields in each laser are in-phase and result in a single-lobed output radiation pattern. The lower two figures show the energetically favored situation, in which the fields in adjacent lasers are out-of-phase, yielding a twin-lobed far-field pattern which is far less useful for most applications. This second case is energetically preferred because the field can go through a null in the absorbing regions between the lasers.

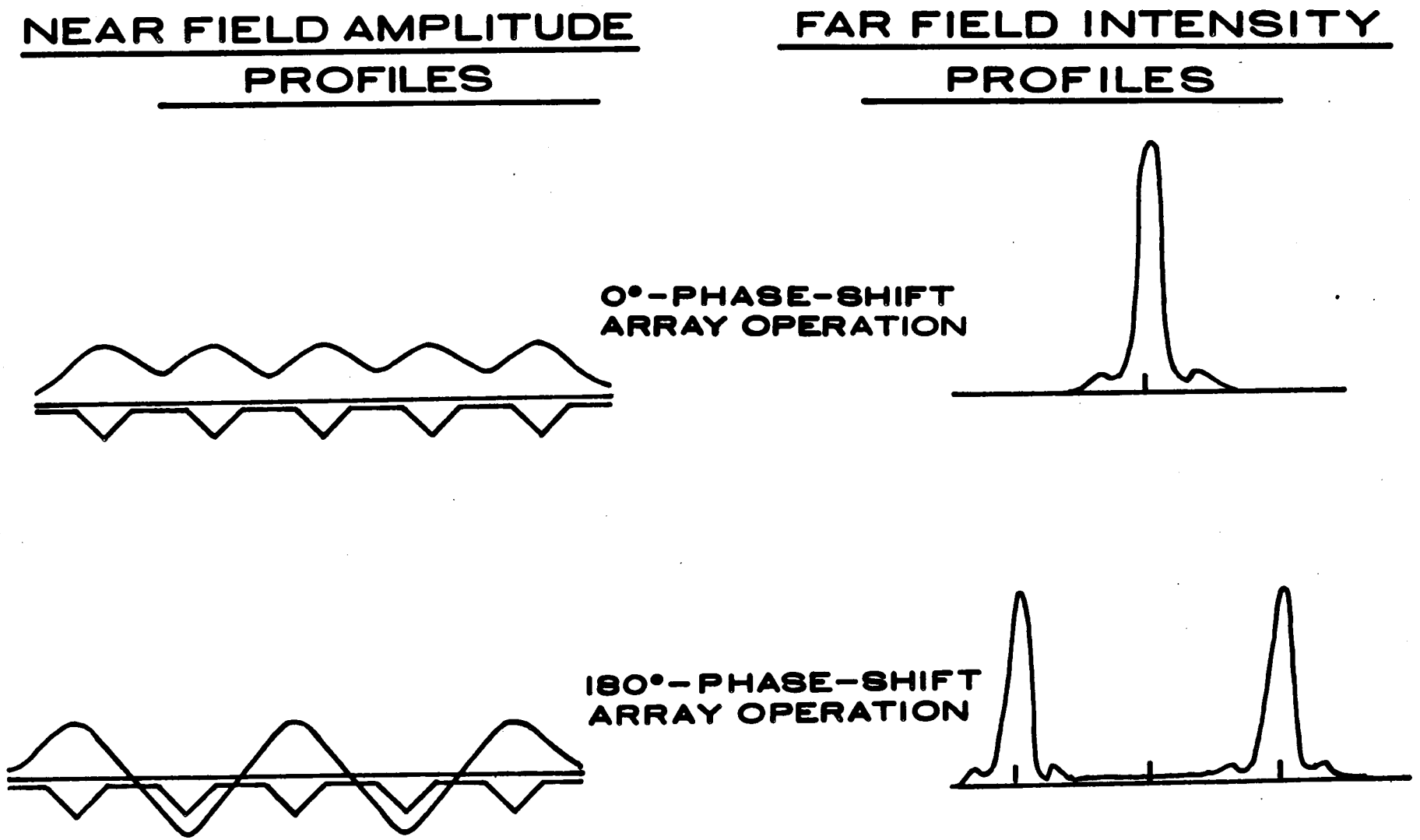
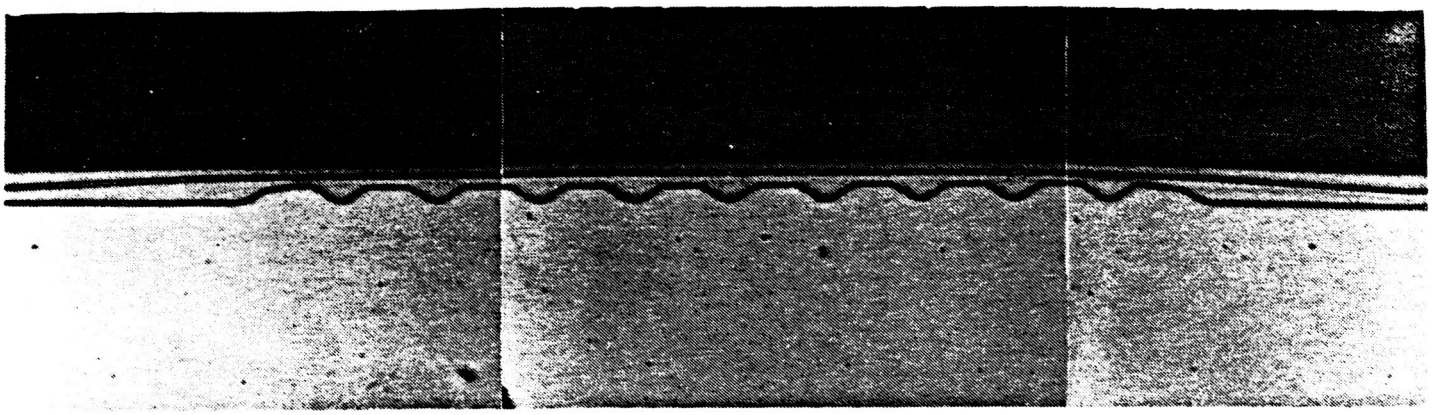

NEAR FIELD AMPLITUDE PROFILES
FAR FIELD INTENSITY PROFILES
0°-PHASE-SHIFT ARRAY OPERATION
180°-PHASE-SHIFT ARRAY OPERATION

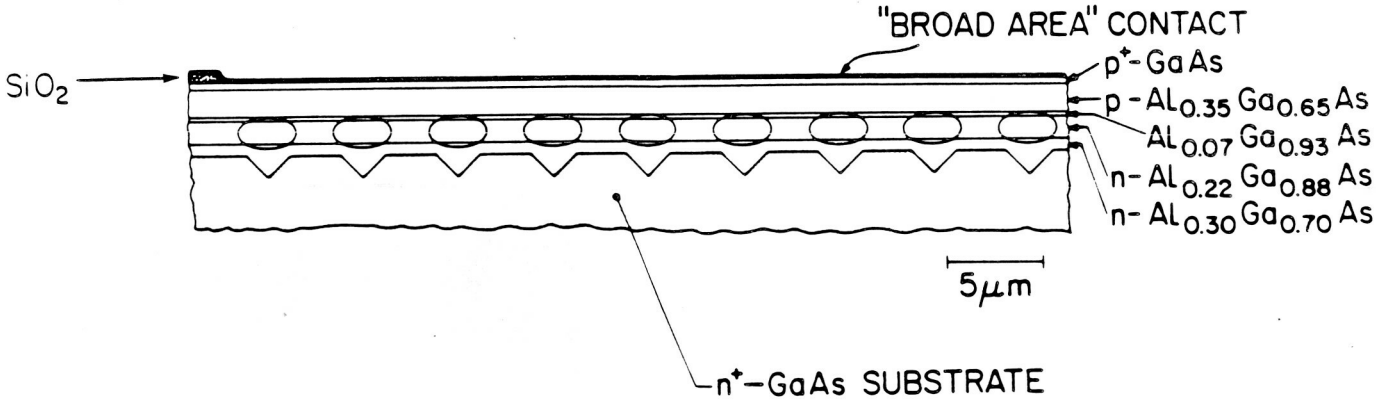
Figure 17

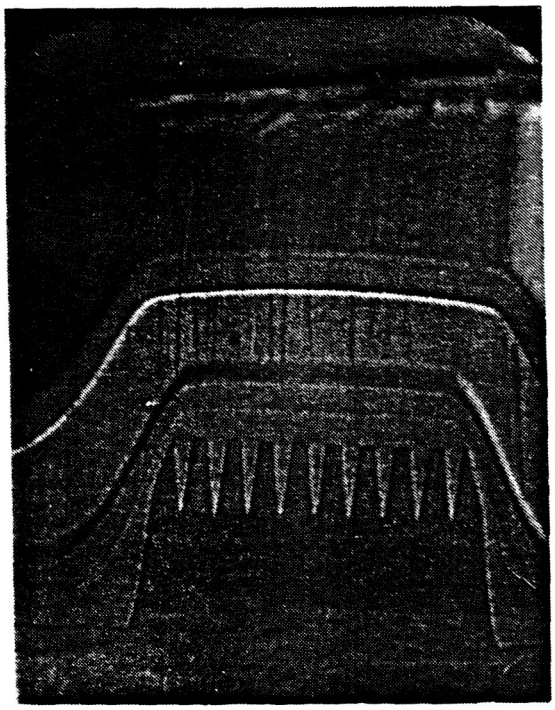
FIGURE 18

This figure shows a cross-section microphotograph, a schematic drawing and a 5° angle lap microphotograph of a nine-element CSP-LOC phase-locked array fabricated at RCA Laboratories. The inclusion of the LOC layer enhances the leakage of the optical modes in a laser to adjacent waveguides. The CSP structure is suited to phase-locked array applications because the channel over which it is grown is relatively narrow. CDH structures are grown over twin dovetail channels, typically 32 μm apart, which is too great a distance to effect significant coupling.

CPS-LOC PHASE-LOCKED ARRAY







5° ANGLE LAP

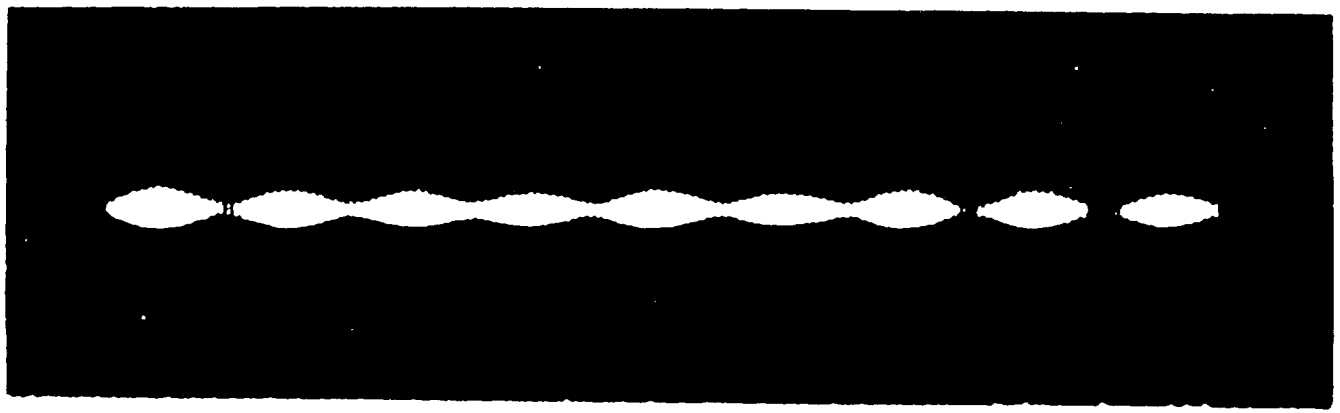
Figure 18

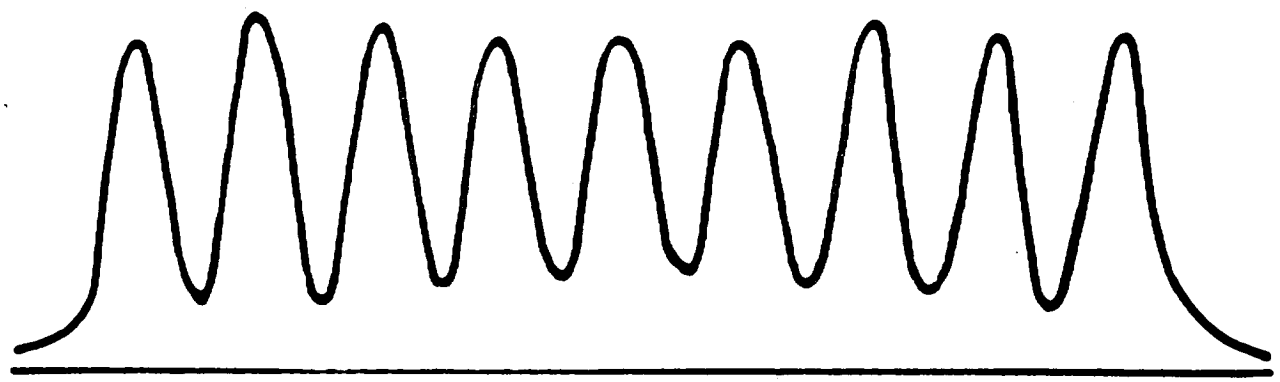
10-192

FIGURE 19

Shown are a microphotograph and densitometer trace of the near-field intensity profiles from a nine-element CSP-LOC phase-locked array having 5 μm inter-element separation. The intensities achieved by each element are quite uniform.

PHASE-LOCKED-ARRAY NEAR FIELD





5 μm

Figure 19

10-194

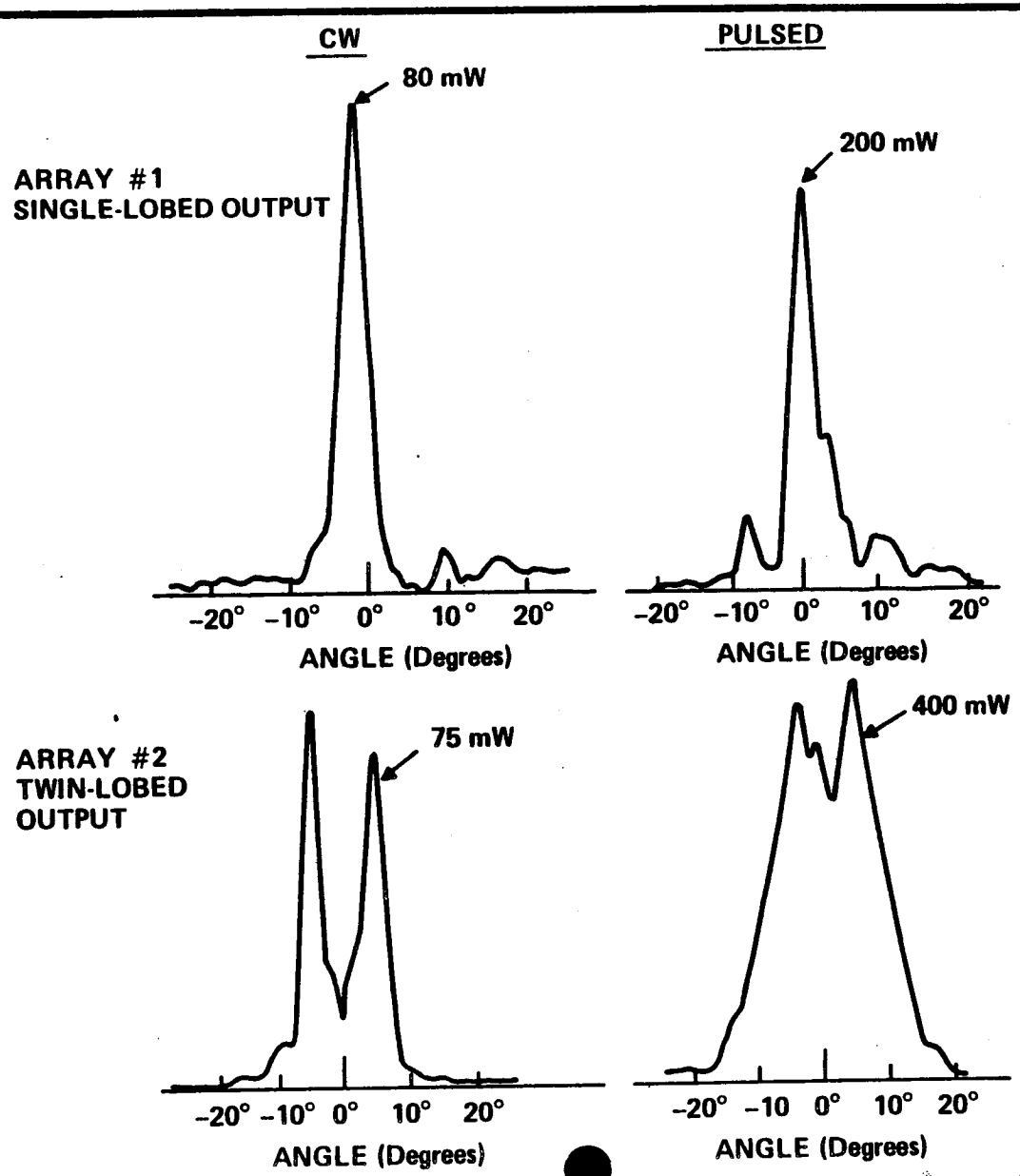
FIGURE 20

The best far-field patterns achieved thus far from CSP-LOC arrays at RCA Laboratories are shown under both cw and low-duty-cycle pulse operation. One such array achieved 80 mW cw and and 200 mW at 0.1% duty-cycle in a single-lobed beam. Another array achieved 75 mW cw and 400 mW pulse, but in a twin-lobed output pattern. Unfortunately, the latter are far more prevalent. Recent computer models, however, have shown how this basic structure can be designed to enhance the probability of single-lobed output.

Figure 20

RCA Laboratories

CSP-LOC Phased-Locked Array Far-Field Patterns



10-196

FIGURE 21

The spectral output of such CSP-LOC arrays have shown single-line operation. There is a frequency shift with power, but this appears to be a smooth transition. No evidence of mode-hopping, a source of noise in optical communications systems, has been observed.

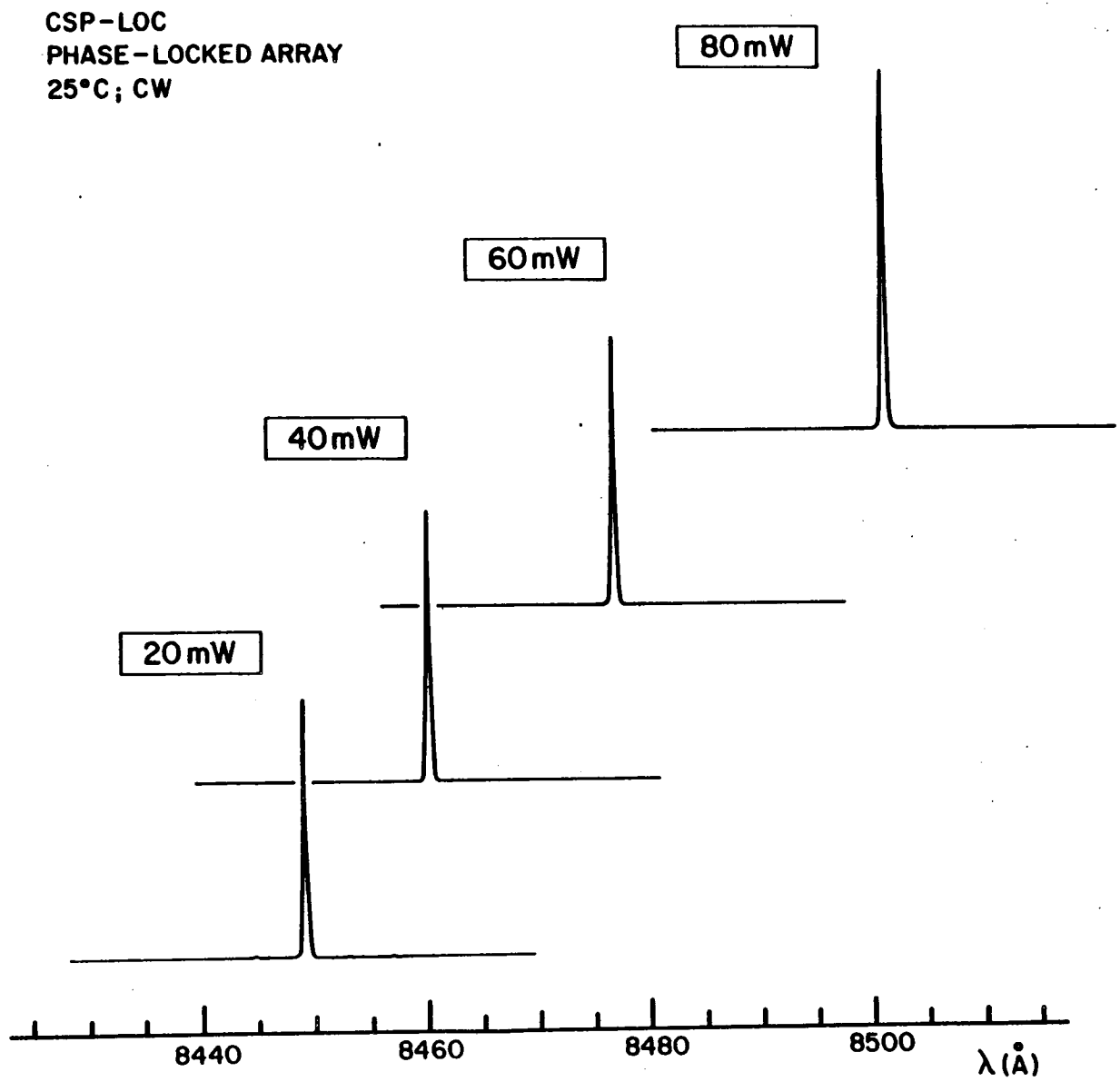

CSP-LOC
PHASE-LOCKED ARRAY
25°C; CW
80mW
60mW
40mW
20mW
8440
8460
8480
8500
λ(Å)

Figure 21

SHAPES LASER RANGEFINDER AND NEW CONCEPTS FOR A RENDEZVOUS & PROXIMITY OPERATIONS SENSOR

PRESENTED TO

RENDEZVOUS AND PROXIMITY OPERATIONS WORKSHOP
JOHNSON SPACE CENTER
FEBRUARY 19–22, 1985

JPL

E. F. TUBBS
J. M. McLAUCHLAN
N. M. NERHEIM

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY

10-199

JPL

SHAPES

(SPATIAL HIGH ACCURACY POSITION ENCODING SENSOR)

- A SENSOR UNDER CURRENT DEVELOPMENT FOR 3-D POSITION SENSING
- CAPABILITIES OF:
  - MULTIPLE TARGETS (20-50)
  - SUB-MILLIMETER ACCURACY
  - REAL TIME OUTPUT DATA RATE (10 READINGS/sec)
- LARGE SPACE STRUCTURES APPLICATIONS INCLUDE:
  - SYSTEMS IDENTIFICATION
  - FIGURE CONTROL
- UTILIZES SEVERAL TECHNIQUES APPLICABLE TO SENSING FOR RENDEZVOUS AND DOCKING
  - MODULATION OF LASER DIODES
  - ULTRA FAST OPTICAL DETECTION FOR RANGING
  - HIGH PRECISION ANGULAR POSITION SENSING WITH CCD's

THE RESEARCH DESCRIBED HERE WAS PERFORMED AT THE
JET PROPULSION LABORATORY, CALIFORNIA INSTITUTE OF TECHNOLOGY
UNDER THE SPONSORSHIP OF THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

SHAPES

Spatial, High-Accuracy Position-Encoding Sensor

Principle of Operation

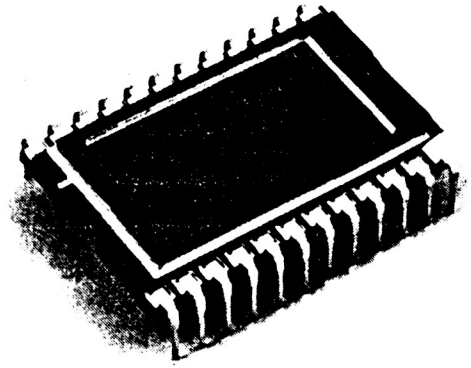
Time of Flight to Many Reflectors Measured by Comparing with Time-Reference Path of Selectable Discrete Fiber-Optics Delays Using a Streak Tube as a Vernier. Lateral Positions Measured by a Second CCD.

Measures

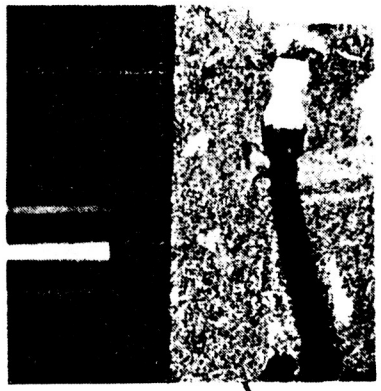
3-D Positions of Multiple Locations to Sub-Millimeter Accuracy at 10 Readings/sec

Applications to Large Space Structures

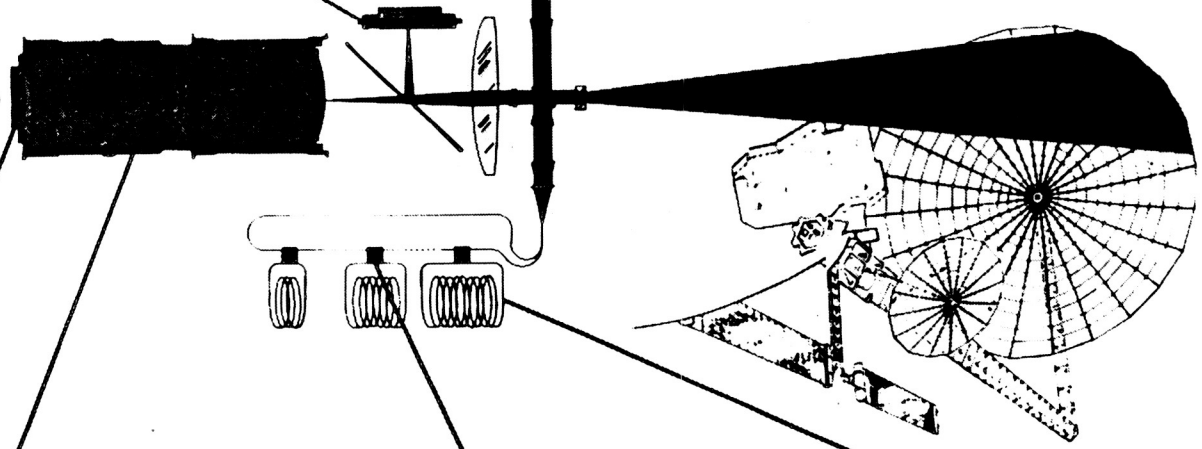
- System Identification
- Stabilization
- Pointing
- Figure Control



Position CCD

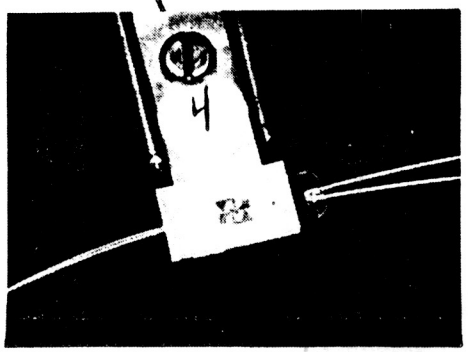


Picosecond-Pulse Laser Diode

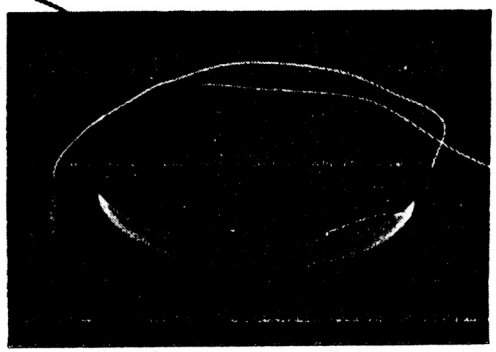


Streak Tube

Integrated-Optics Switches



Fiber-Optics Reference Path



10-201

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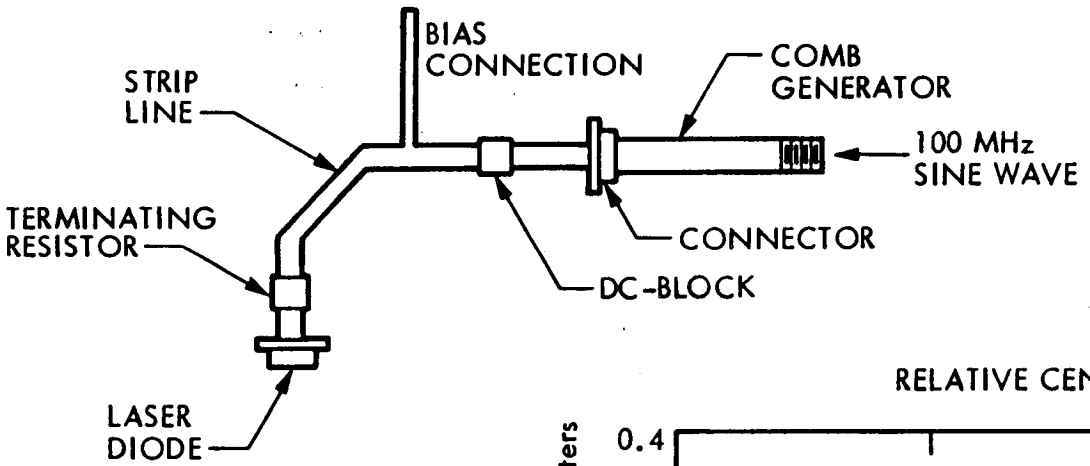
RANGE RESOLUTION CAPABILITIES

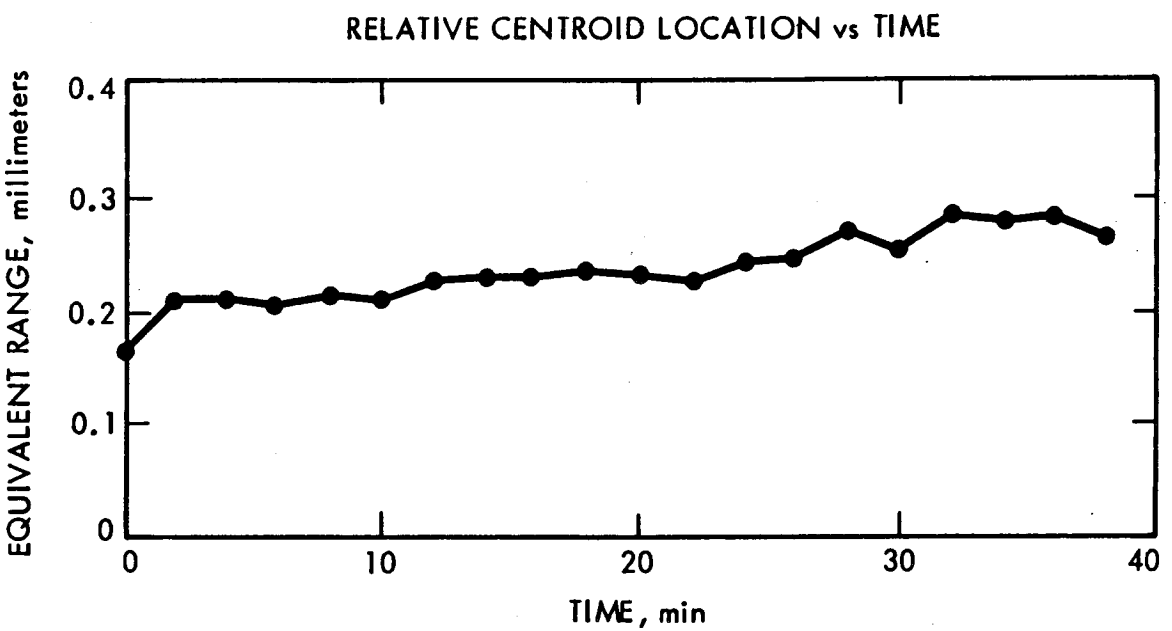
- SHAPES SENSOR OUTPUT RANGE POSITION
  - RANGE RESOLUTION (WITH OPEN LOOP PHASE DRIFT REMOVED) APPROXIMATELY 0.02 millimeters
- RANGE ACCURACY
  - DEPENDENT ON SENSOR IMPLEMENTATION AND MEASURES TAKEN TO STABILIZE DRIFTS AND SELF-CALIBRATION TECHNIQUES
  - WITH SUFFICIENT CARE ACCURACY COULD APPROACH RESOLUTION CAPABILITIES
  - MORE WORK REMAINS TO BE DONE IN THIS AREA

RANGE RESOLUTION CAPABILITIES FROM REPETITIVE SHORT-PULSE OPERATION OF A LASER DIODE



OPERATING CONDITIONS

INPUT POWER	1 W
FREQUENCY	100 MHz
OUTPUT PULSE DURATION (FWHM)	30 psec



JPL

DYNAMIC RANGE SENSING

DEMONSTRATES REAL TIME (8 Hz DATA RATE) PROCESSING OF RANGE DATA (USING 8 BIT PROCESSOR)

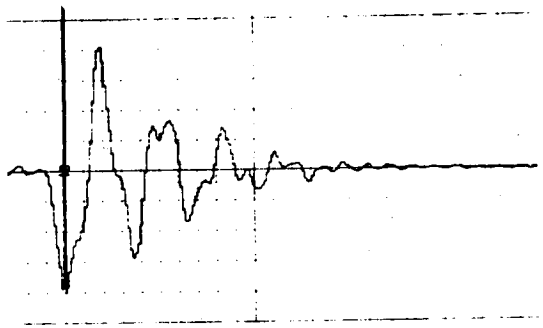
10-204

JPL

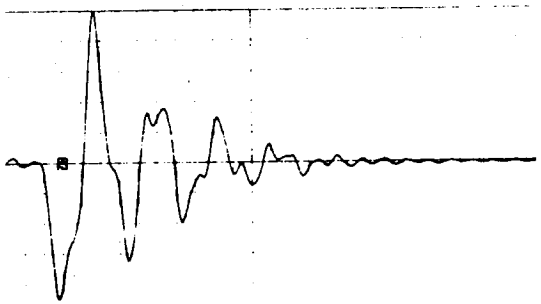
THE FLEXIBLE-BEAM EXPERIMENT WITH REMOTE POSITION SENSING

THE SHAPES (SPATIAL, HIGH-ACCURACY, POSITION-ENCODING SENSOR) SENSOR HAS BEEN COUPLED TO THE JPL FLEXIBLE-BEAM EXPERIMENT TO PROVIDE A REAL-TIME, REMOTELY-SENSED INPUT TO THE BEAM-CONTROL PROCESSOR

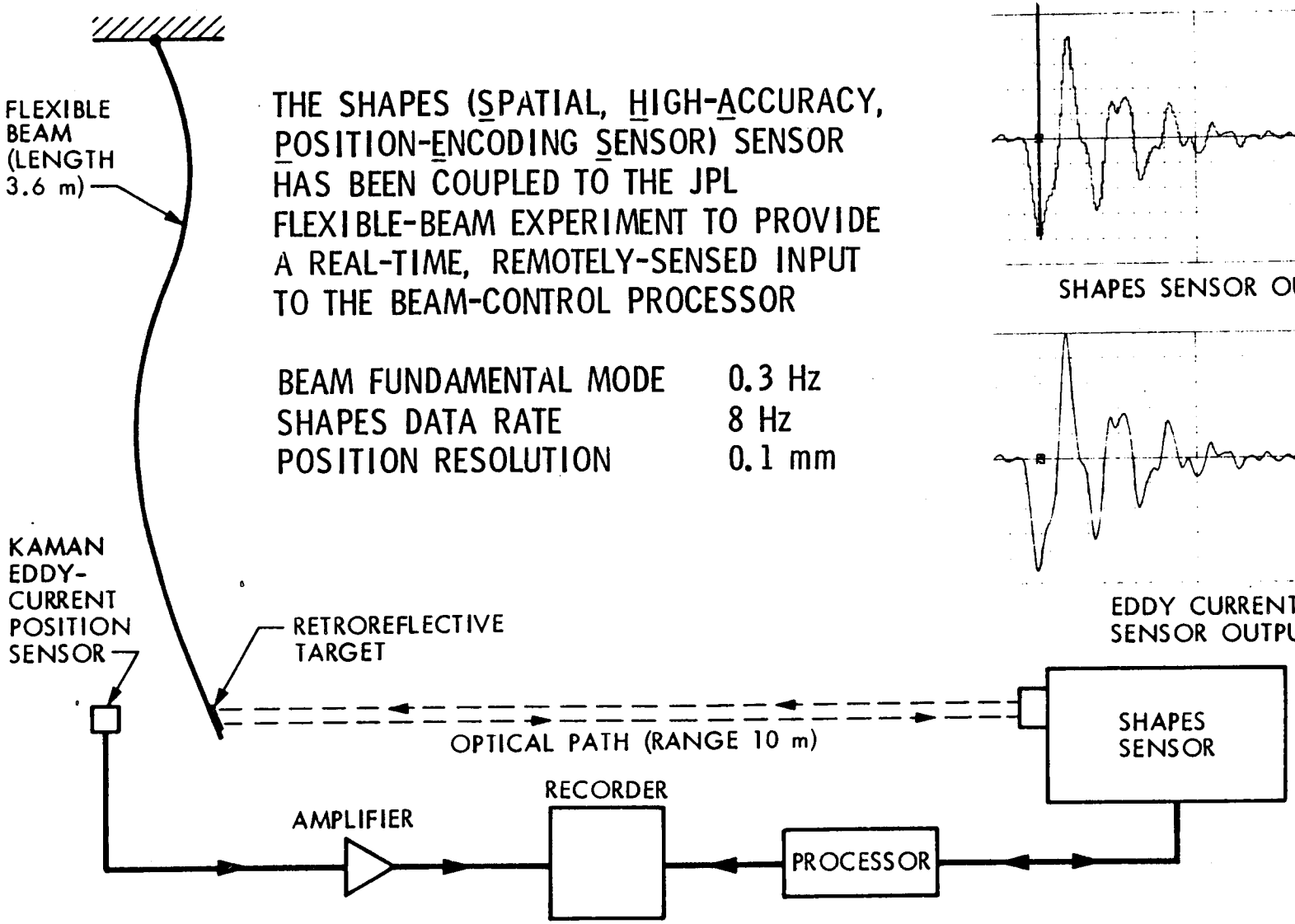
BEAM FUNDAMENTAL MODE	0.3 Hz
SHAPES DATA RATE	8 Hz
POSITION RESOLUTION	0.1 mm



SHAPES SENSOR OUTPUT



EDDY CURRENT SENSOR OUTPUT



10-205

JPL

STATIC RANGE SENSING

- SHOWS CONFIGURATION OF MULTIPLE TARGET (14 TARGETS) SHAPES EXPERIMENT CURRENTLY BEING PERFORMED

- OBJECTIVE TO DEMONSTRATE MULTIPLE TARGET DATA PROCESSING

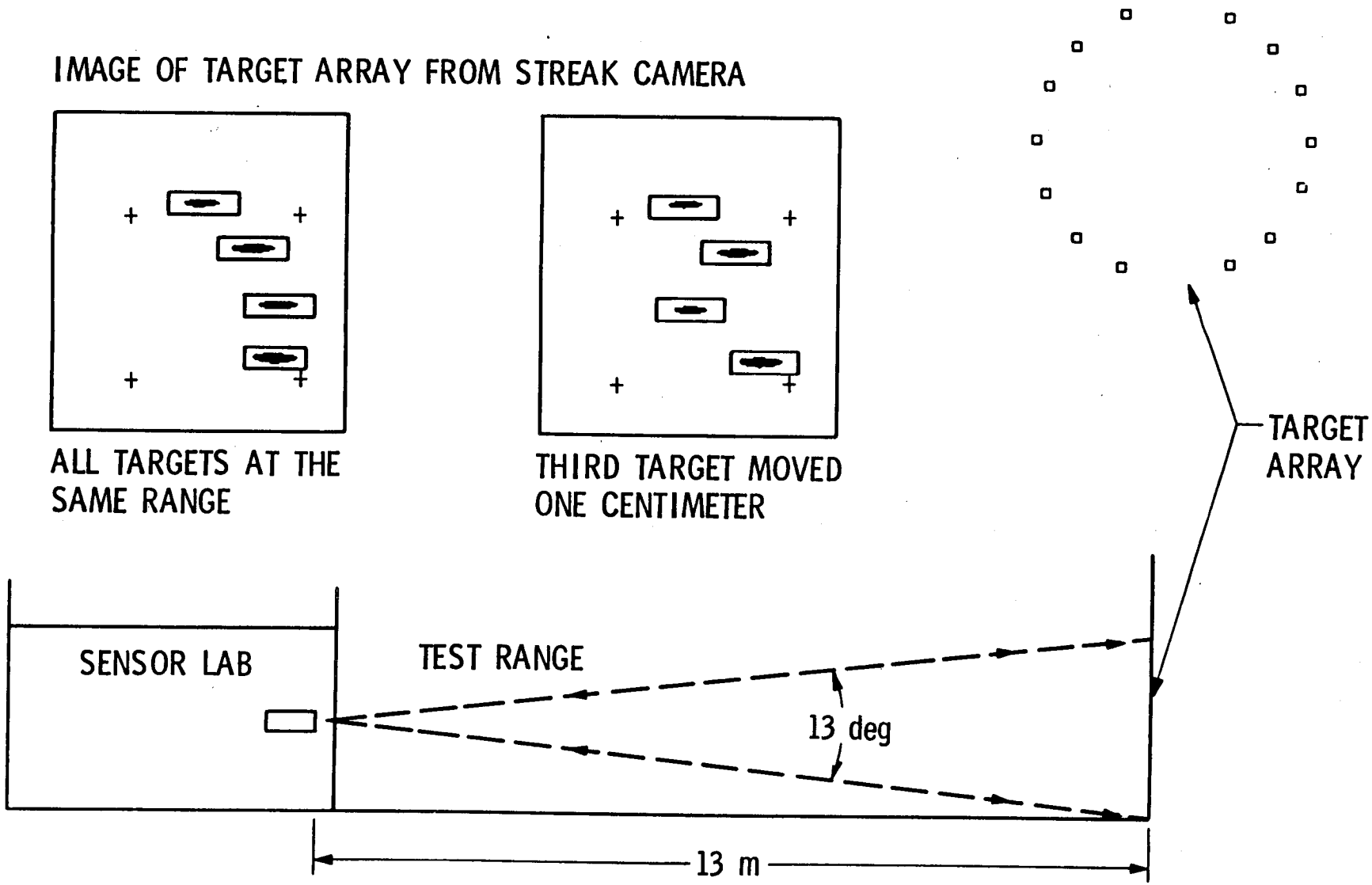
10-206

JPL SHAPES STATIC-RANGING EXPERIMENT

IMAGE OF TARGET ARRAY FROM STREAK CAMERA

ALL TARGETS AT THE SAME RANGE

THIRD TARGET MOVED ONE CENTIMETER



10-207

JPL

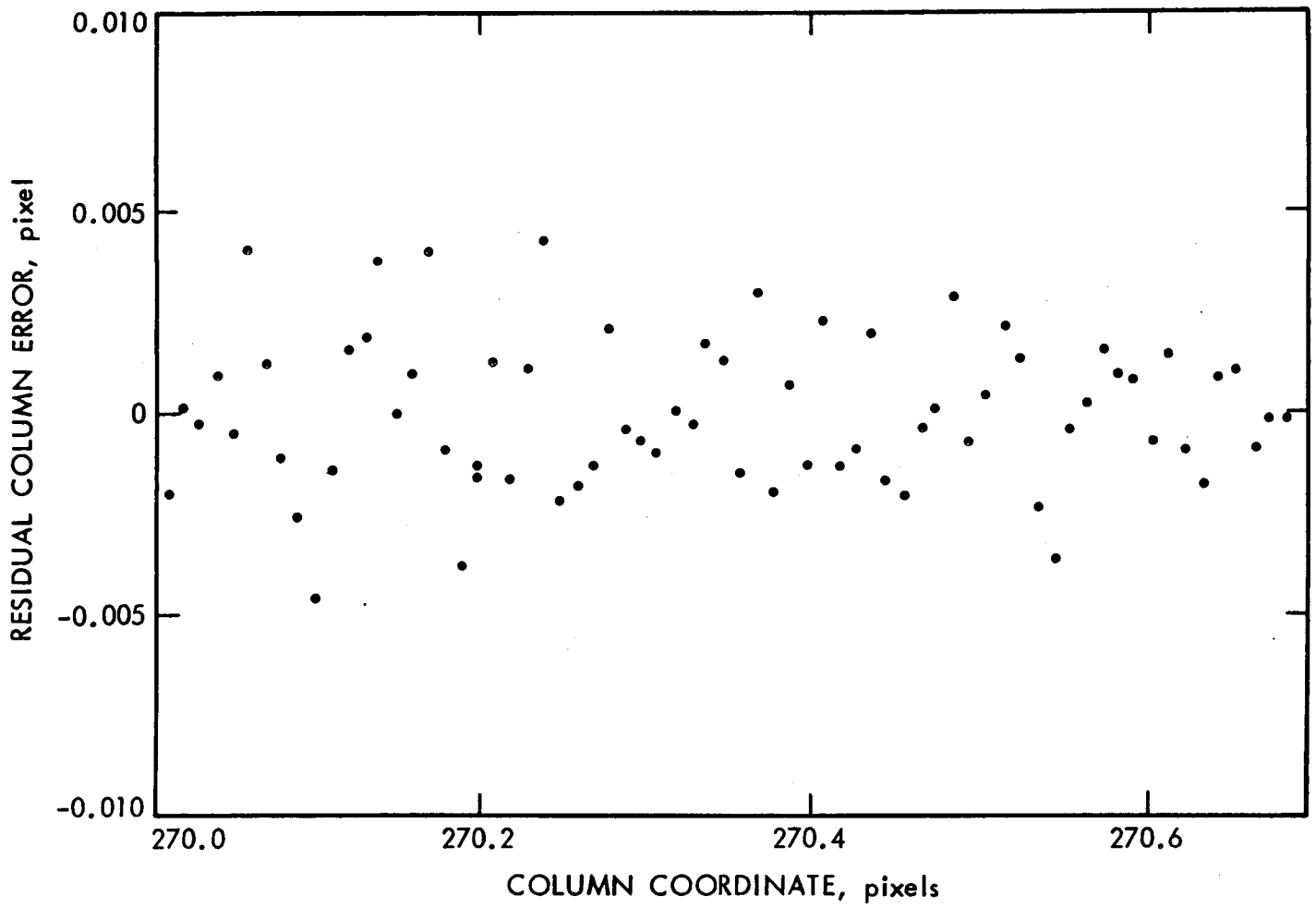
CCD POSITION ACCURACY

- POSITION ACCURACY BETTER THAN 0.005 pixel (OVER LOCAL AREA)

10-208

JPL ASTROS CCD STAR TRACKER TEST RESULTS

COLUMN ERROR AFTER CALIBRATION CORRECTION HAS BEEN APPLIED AS A FUNCTION OF CENTROID LOCATION WITHIN A PIXEL



JPL

APPLYING SHAPES TECHNIQUES TO RENDEZVOUS AND DOCKING

PRELIMINARY CONSIDERATIONS

SEARCH AND ACQUISITION

FOV	10 deg
RANGE	1 km PLUS
BACKGROUND	SUNLIT EARTH

POSITION MEASUREMENT AND TRACKING

	LIMITS	ACCURACY
RANGE	2 m to 1 km	1 cm
RANGE RATE	± 50 m/s	1 cm/s
BEARING	± 10 deg	0.5 deg
BEARING RATE	± 2 deg/s	5 $\widehat{\text{sec}}$/s

ATTITUDE DETERMINATION

	LIMITS	ACCURACY
PITCH AND YAW	± 20 deg	1 deg
ROLL	360 deg	1 deg

10-210

JPL

TECHNICAL APPROACH FOR RENDEZVOUS AND DOCKING SENSING

- 3 RETROREFLECTORS ON TARGET VEHICLE
  - RETROREFLECTOR SPACING ~ 10 cm
    (REDUCES MOUNTING CONSTRAINTS ON TARGET VEHICLE)
  - RETROREFLECTORS SPECTRALLY CODED
    (PERMITS NONINTERFERING MEASUREMENT OF EACH RETROREFLECTOR, AT SMALL ANGULAR SEPARATIONS, DUE TO VEHICLE ATTITUDE OR EXTENDED RANGE)

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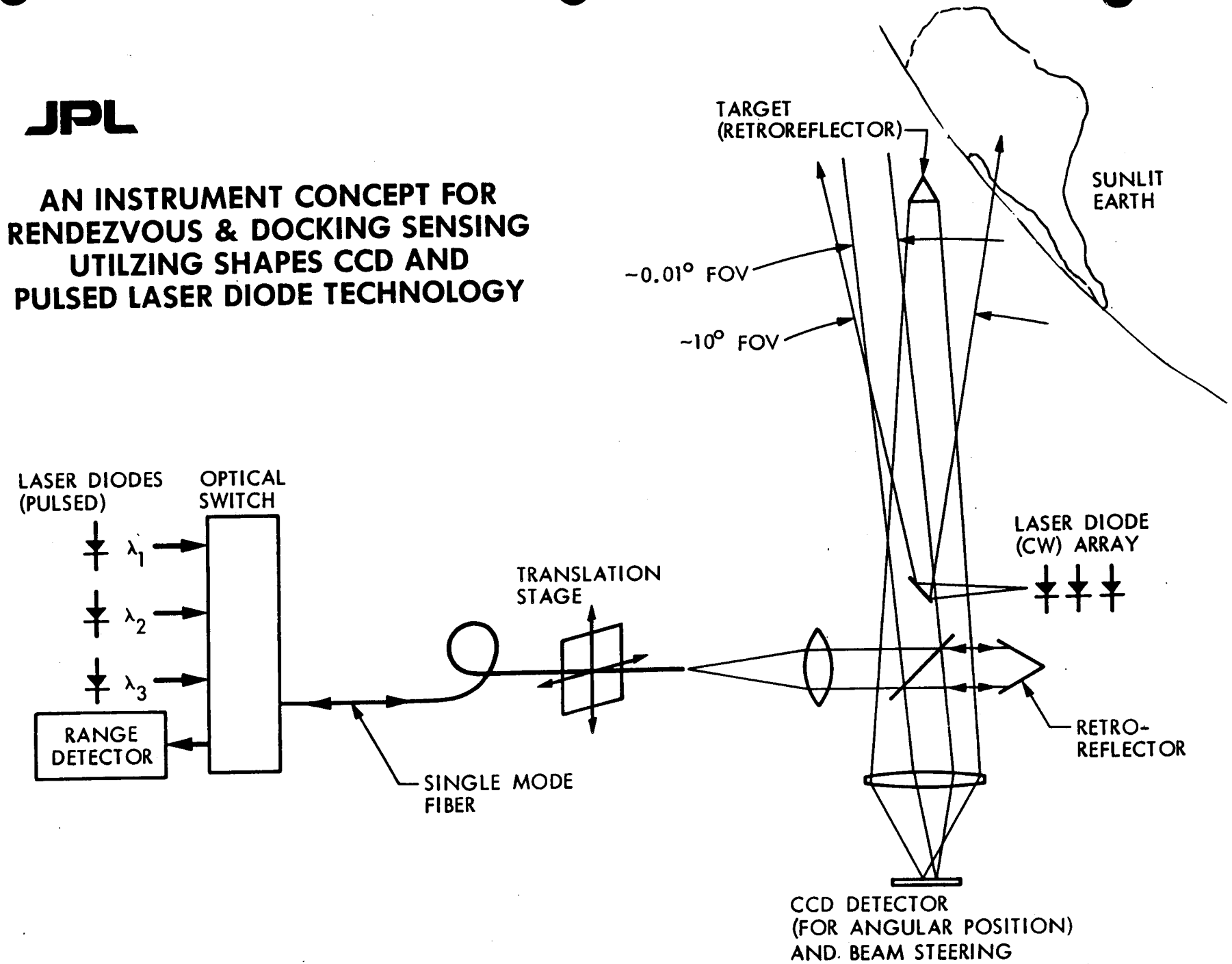
AN INSTRUMENT CONCEPT FOR RENDEZVOUS AND DOCKING SENSING

- ACQUISITION AND ANGULAR POSITION TRACKING
  - MULTIPLE, CW OPERATED, LASER DIODES PROVIDE POWER FOR WIDE FOV (10°) AND 1 km PLUS RANGE
  - CCD PROVIDES
    - SMALL FOV PER PIXEL ($\sim 0.02^{o}$) FOR BACKGROUND SUPPRESSION
    - MEASURES RELATIVE POSITION OF ADJACENT RETROREFLECTORS TO HIGH ACCURACY (e.g., 0.005 pixel = $\sim 2\ \mu$rad)
- RANGE MEASUREMENT
  - NARROW BEAMWIDTH OF RANGE ILLUMINATOR ($\sim 0.01^{o}$) PROVIDES HIGH BEAM POWER FOR EXTENDED RANGE AND ALSO PERMITS LOW DUTY CYCLE (0.01) FOR PULSED OPERATION
  - PULSED OPERATION ($\sim$30 ps PULSE) PERMITS PRECISION RANGING AND RANGE GATING TO ELIMINATE INSTRUMENT BACKSCATTER FROM OUTGOING PULSES
  - PRECISION SERVO POINTING OF NARROW BEAM RANGE ILLUMINATOR PROVIDED BY SENSING OF DIFFERENTIAL POSITIONS OF OUTGOING RANGE BEAM AND RETURN ANGULAR POSITION BEAM ON CCD
  - SHARED RANGING ILLUMINATION AND RECEIVING WITH SINGLE MODE FIBER APERTURE PROVIDES RANGE DETECTOR WITH NARROW FOV ($\sim 0.01^{o}$) FOR BACKGROUND SUPPRESSION
- RANGE DETECTOR
  - SEVERAL TECHNIQUES UNDERGOING TRADEOFF STUDIES AND EXPERIMENTATION FOR RANGE GATING/SINGLE PROCESSING
    - OPTICAL GATING WITH INTEGRATED OPTICS PICOSECOND SWITCHES
    - PICOSECOND PHOTODETECTORS AND SUBSEQUENT PICOSECOND PHOTOCONDUCTIVE ELECTRONIC SIGNAL SAMPLING
    - STREAK TUBE DETECTION
  - ALL TECHNIQUES HAVE CAPABILITIES OF SUBMILLIMETER ACCURACY BUT HAVE SIGNIFICANT DIFFERENCES IN IMPLEMENTATION CONSIDERATIONS

JPL

AN INSTRUMENT CONCEPT FOR RENDEZVOUS & DOCKING SENSING UTILZING SHAPES CCD AND PULSED LASER DIODE TECHNOLOGY



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SUMMARY

- A CONCEPT, UNDER CURRENT STUDY, HAS BEEN PRESENTED THAT OFFERS POTENTIALLY ATTRACTIVE PERFORMANCE FEATURES
  - MEASURES BOTH TARGET POSITION AND ATTITUDE AT RANGE OF 1 km PLUS AGAINST EARTH BACKGROUND (CAN BE SIGNIFICANTLY INCREASED WITH NARROWER ACQUISITION FOV)
  - PROVIDES HIGH ANGULAR POSITION AND RANGE ACCURACIES
  - IMPOSES ONLY MODERATE MOUNTING CONSTRAINTS ON TARGET STRUCTURE (i.e., 10 cm RETROREFLECTOR SPACING)
- SEMI-CONDUCTOR LASER DIODE ILLUMINATORS COMBINED WITH TARGET RETROREFLECTORS CAN BE IMPLEMENTED IN MANY DIFFERENT TYPES OF COMPONENT AND SYSTEM CONFIGURATIONS FOR RENDEZVOUS AND DOCKING SENSING
- ADVANCED DEVELOPMENT WORK, NOW IN PROGRESS, WILL ENABLE BETTER UNDERSTANDING OF THE TECHNIQUES FOR ACHIEVING MAXIMUM PERFORMANCE CAPABILITIES WITH THIS TECHNOLOGY

10-214

SESSION 11 - DATA SYSTEMS

11-1. "The Effect of Rendezvous and Proximity Operations on the Space Station Data Management System Architecture" - Wally Clark/TRW

11-2. "The Effect of Rendezvous and Proximity Operations on the Space Station Data Management System Architecture" - Glen Love/McDonnell Douglas

11-3. "High Performance Networks for Combined Video, Voice, and Data" - Nicholas Murray, Herbert Hendricks, and Edwin Foundriat/NASA LaRC

11-4. "Video Image Processing for Space Station Operations" - Kenneth Hoyme, Sudhakar Yalamanchili, and Richard Fundakowski/Honeywell Systems and Research Center

11-5. "Signal Processing Elements and Computers for Proximity Operations" - H. Benz/NASA LaRC

11-6. "Optical Mass Storage Ssytems" - Gerald Claffie/RCA Government Systems Division

TRW

The Effect of Rendezvous and Proximity Operations on the Space Station Data Management System Architecture

BY

WALLY CLARK

FEDERAL SYSTEMS DIVISION

TRW SPACE & TECHNOLOGY GROUP

REDONDO BEACH, CA

PREPARED FOR PRESENTATION AT NASA/JSC

WORKSHOP ON PROXIMITY OPERATIONS

HOUSTON, TX

19-22 FEBRUARY 1985

Enclosure 1

Outline

TRW

- Proximity operations as seen from SSDS viewpoint
- SSDS involvement in proximity operations
- SSDS data management and processing

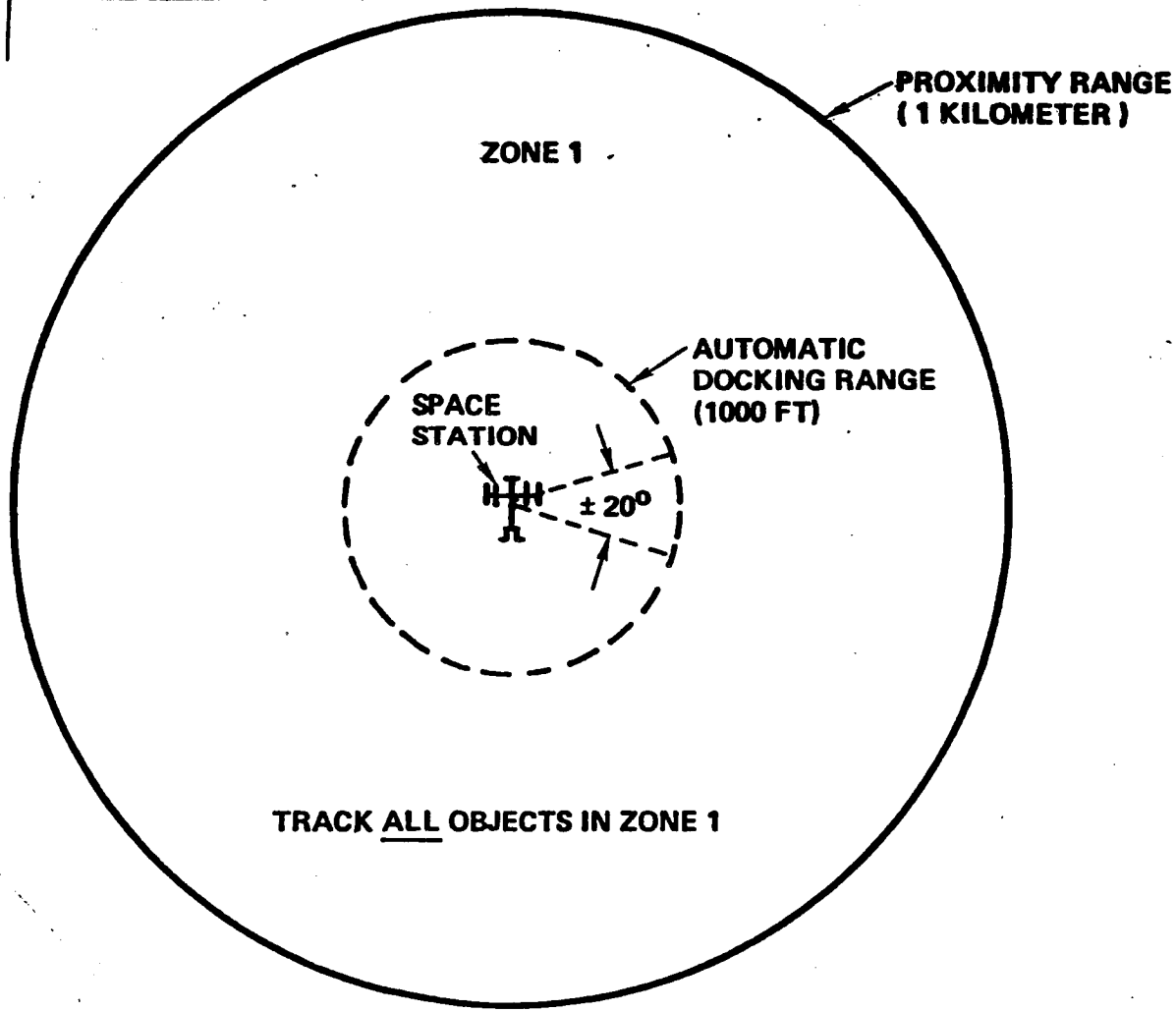
Definitions

TRW

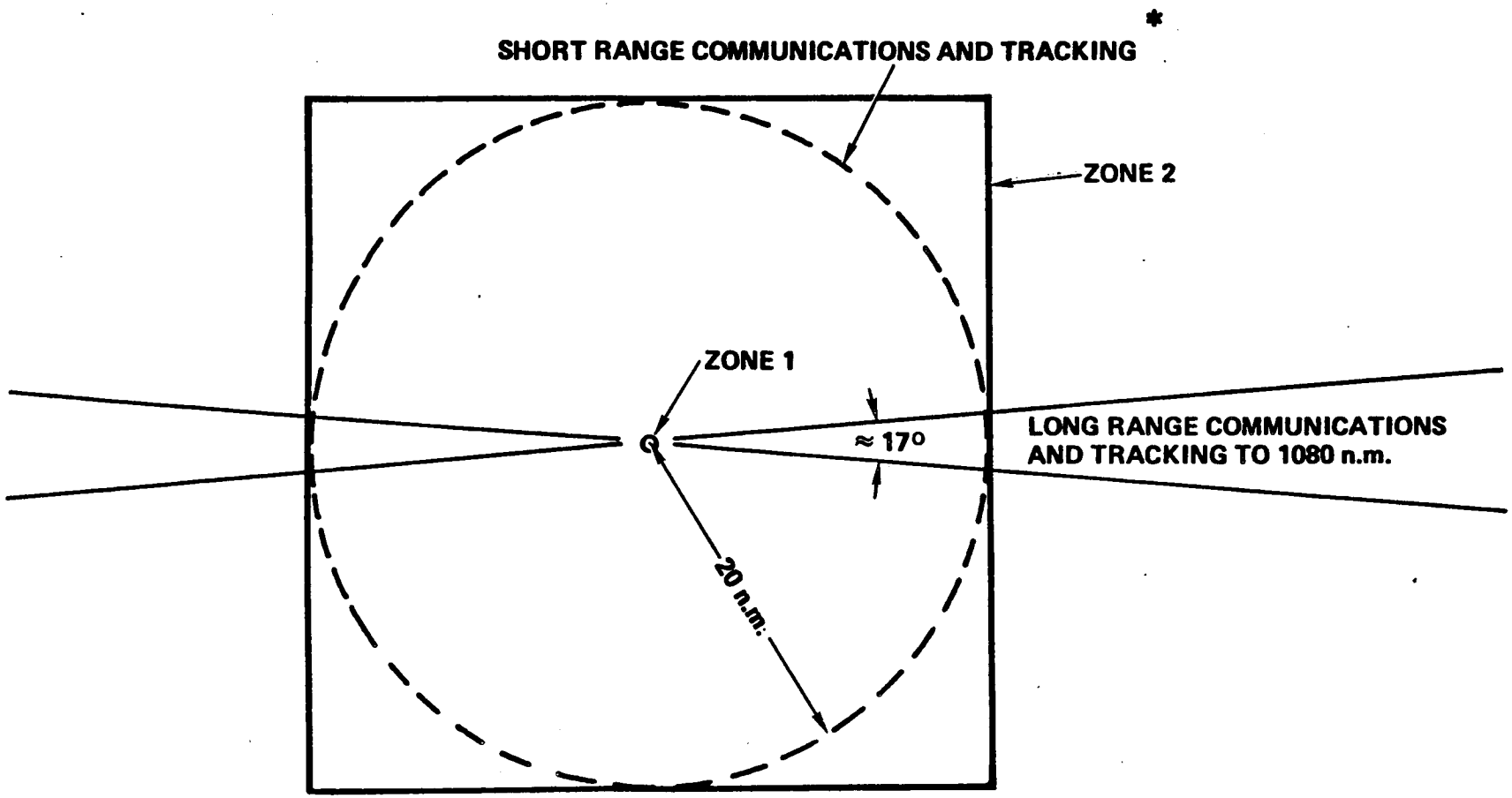
- Proximity operations
  - All detached operations within 20 n.m. of space station
  - All maneuvers where two vehicles are in visual contact. Maneuvers include stationkeeping, transitions to offset points, approaches, departures, flyarounds, and docking

- Rendezvous
  - Maneuvering of two space vehicles into the same orbit and orbital position

Zone 1 Characteristics

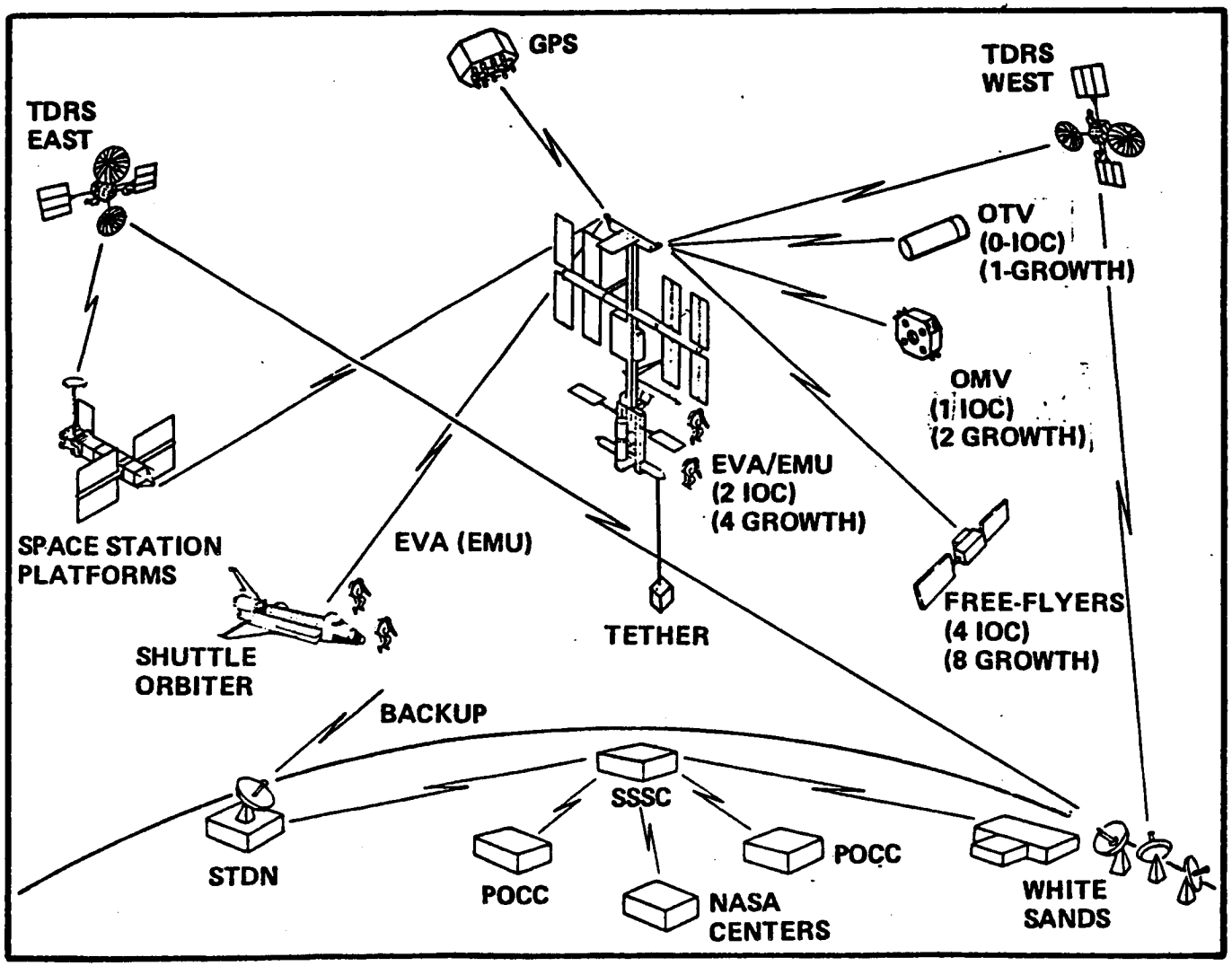


Zone 2 Characteristics



*COOPERATIVE TARGETS

Systems Involved in Proximity Operations



TRW

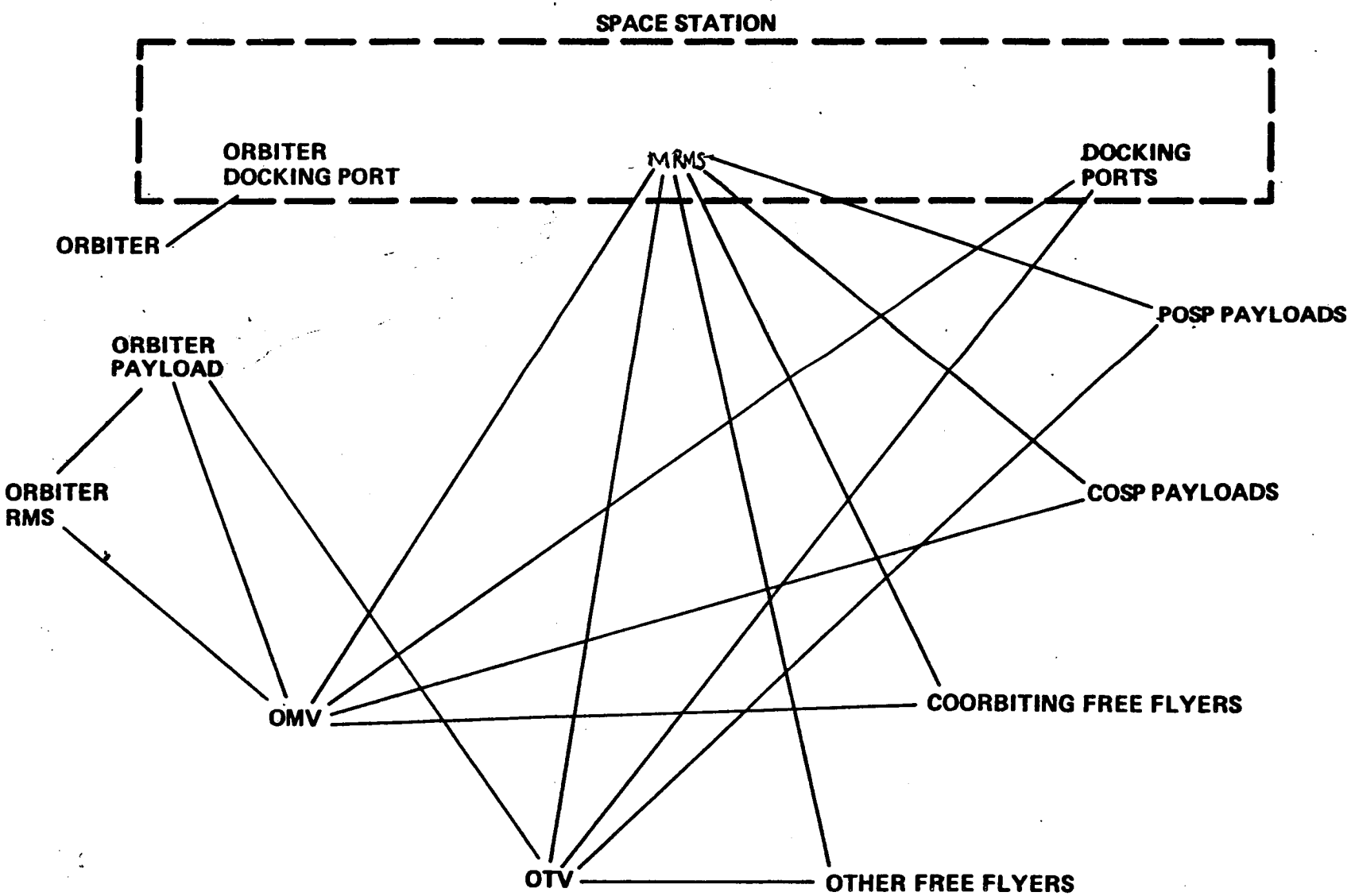
Traffic Estimates (GROWTH CONFIGURATION)

• EVA	One mission/day	Duration: 6 hours
• RMS	Two relocations*/day/RMS (Two RMS)	Duration: 80 minutes/day
• OMV	Three missions/month**	Duration: 24 hours/month
• OTV	One mission/month	Duration: 8 hours/month
• Orbiter	One mission/90 days	Duration: 7 days (24 hrs undocked)
• Free flyers	(Dumb type) 4 ea stationkeeping	Duration: Continuous
• Free flyers	(Smart type) 4 ea stationkeeping	Duration: Continuous
• Tethers	Ten deployment/retrievals per month	Duration: one hour

* 100 ft relocation @ 1 inch/sec

** Assumes three free flyers must be retrieved every 90 days prior to space station reboost, in addition to normal routine. Each mission involves 8 hours of close proximity flying

Docking and Tending Combinations

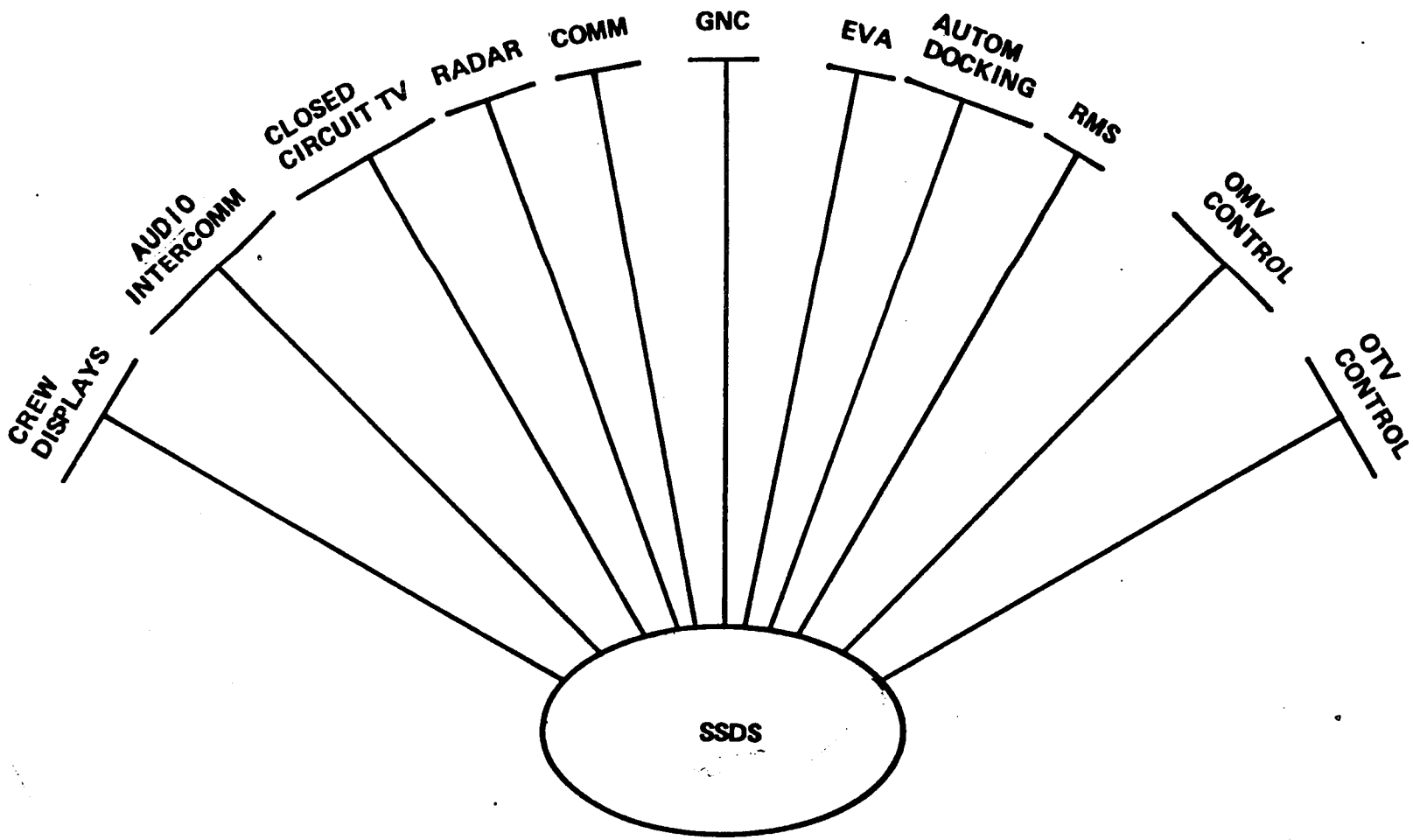


Outline

TRW

- Proximity operations as seen from SSDS viewpoint
- SSDS involvement in proximity operations
- SSDS data management and processing

Space Station Systems Involved in Proximity Operations

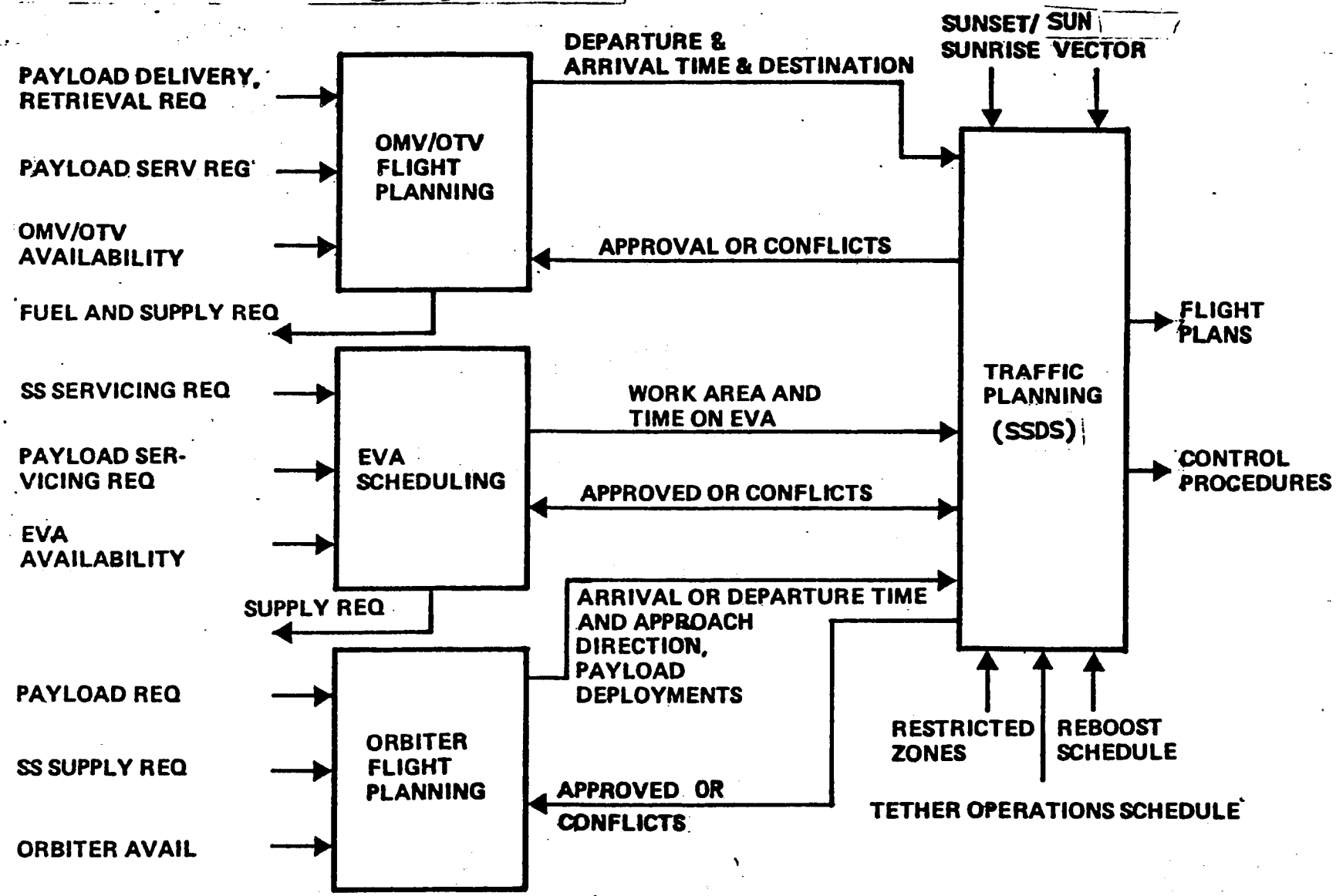


SSDS Involvement in Proximity Operations

TRW

- Traffic planning
- Traffic control
- GN support
- Core systems control

Traffic Planning by SSDS

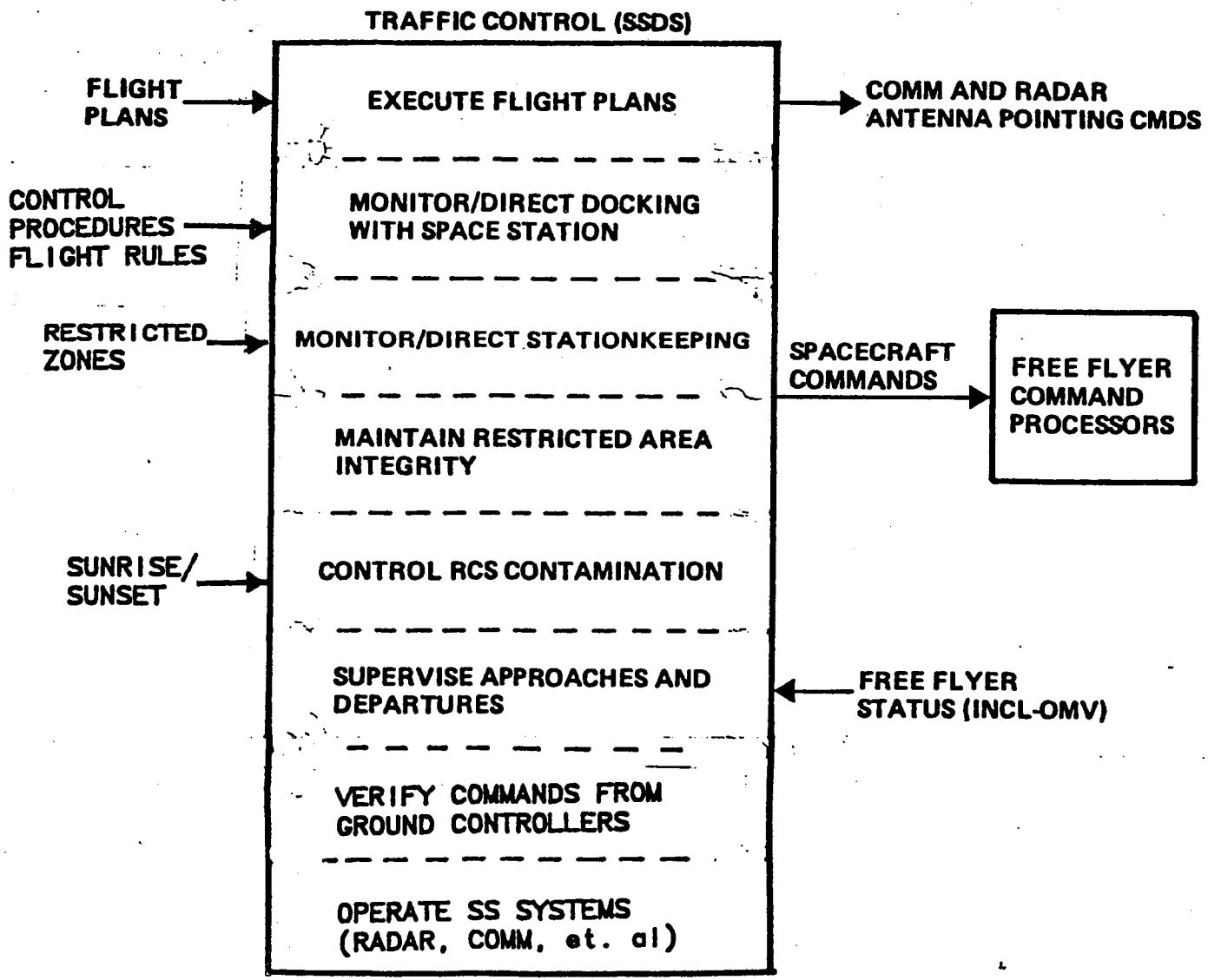


SSDS Involvement in Proximity Operations

TRW

- Traffic planning
- Traffic control
- GN support
- Core systems control

Traffic Control by SSDS



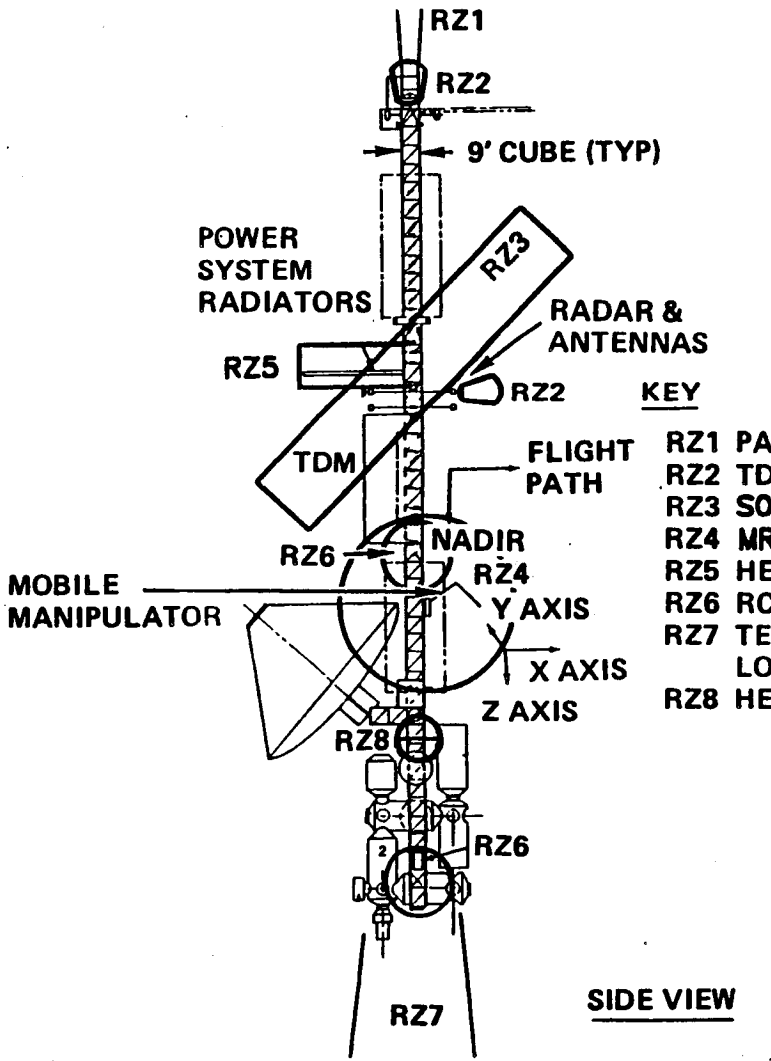
TRW

Restricted Zones

- Payload look directions (mostly vertical)
- MRMS operating area
- RCS impingement area
- Solar panel rotation (β) zone
- Thermal radiation safety zone
- Tether operations zone (directly below SS)
- Approach/departure corridors (to 20 n.m.)
- Docking system approach path limits (to 1000 ft)
- Antennae patterns (TDRSS and radar only)

* Operations and therefore zone restrictions may vary during reboost

Restricted Zones, Side View



SIDE VIEW

KEY

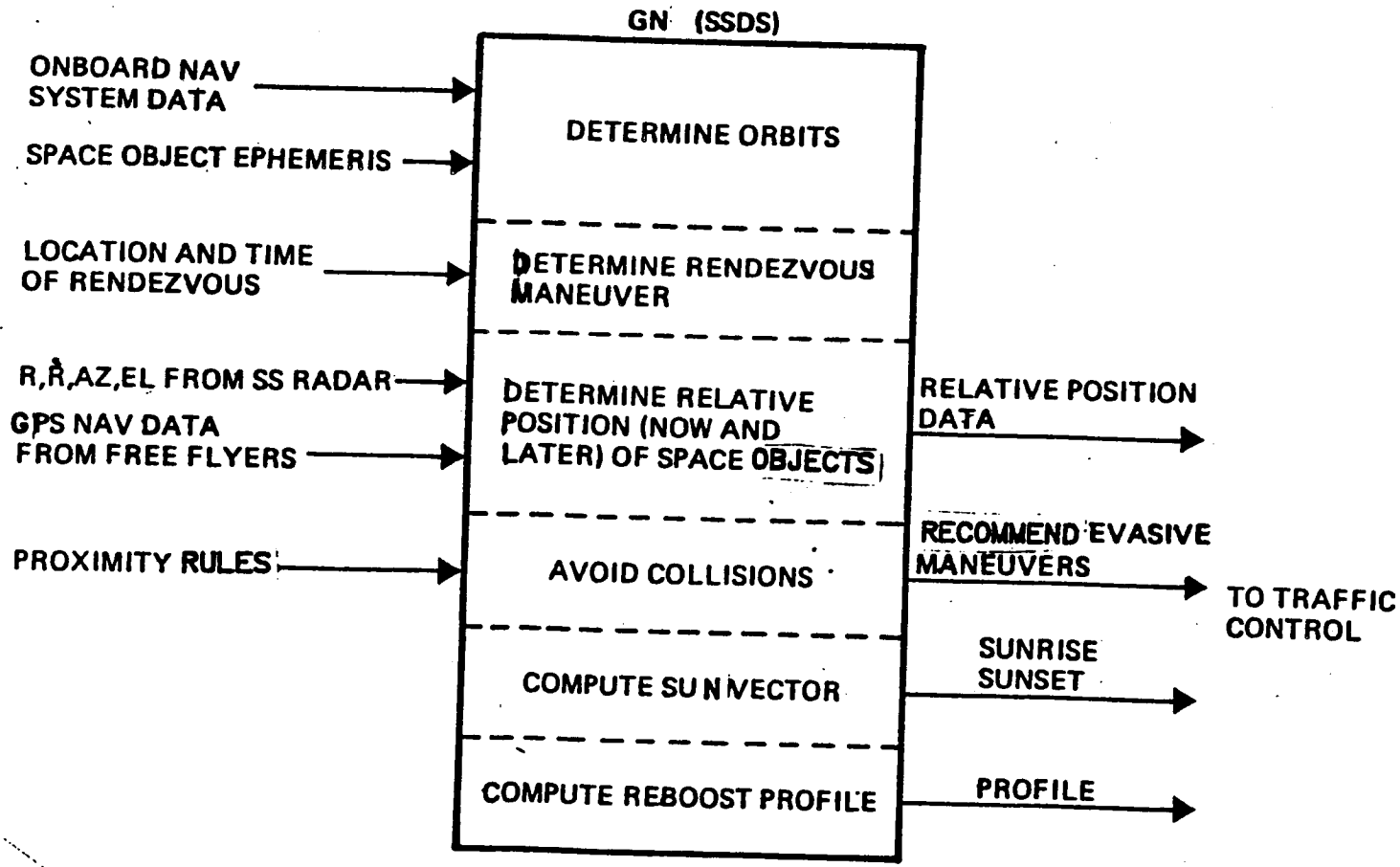
RZ1 PAYLOAD LOOK ZONE
RZ2 TDRSS ANTENNA PATTERN
RZ3 SOLAR PANEL ROTATION ZONE
RZ4 MRMS CLEARANCE ZONE
RZ5 HEAT RADIATION ZONE
RZ6 RCS BBST ZONES
RZ7 TETHER OPS PAYLOAD LOOK ZONE
RZ8 HEAT RADIATION ZONE

SSDS Involvement in Proximity Operations

TRW

- Traffic planning
- Traffic control
- GN support
- Core systems control

SSDS GN Support of Proximity Operations

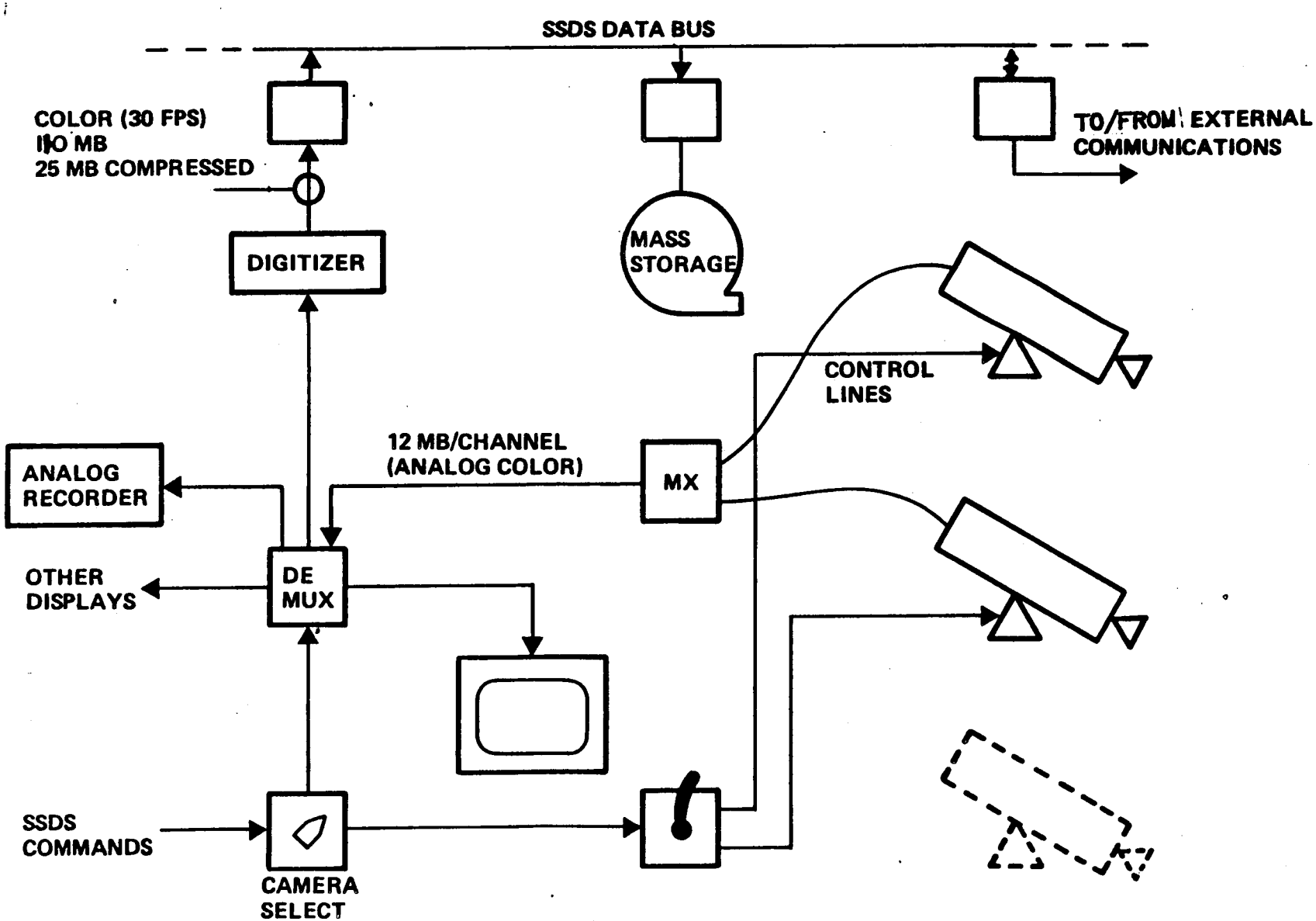


SSDS Involvement in Proximity Operations

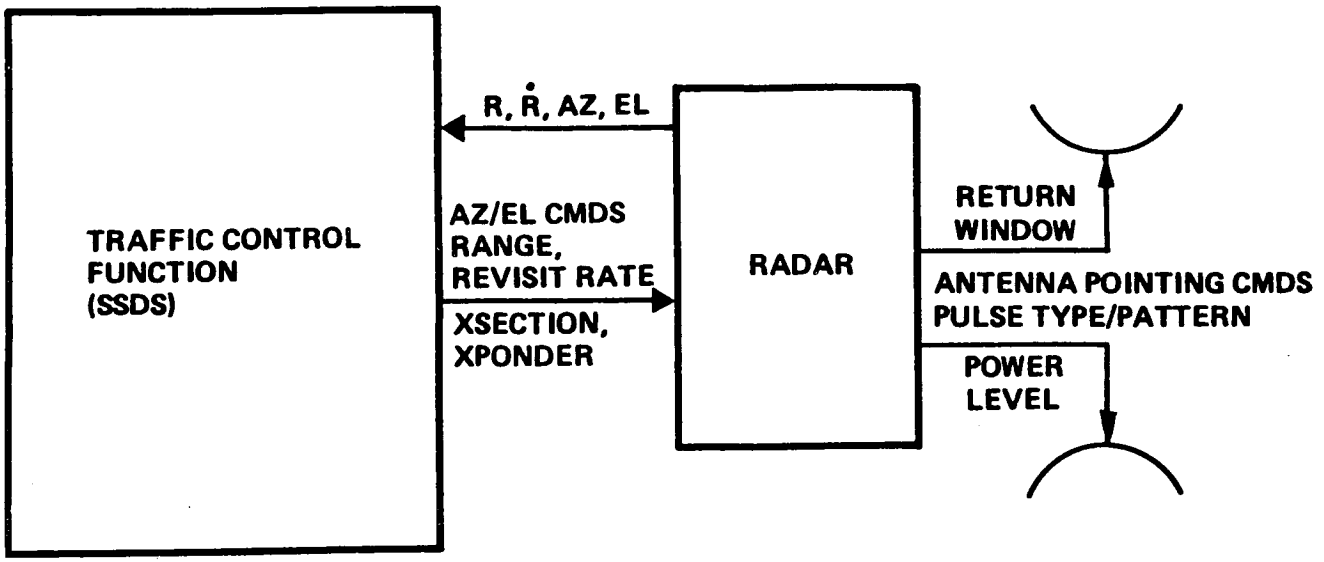
TRW

- Traffic planning
- Traffic control
- GN support
- Core systems control

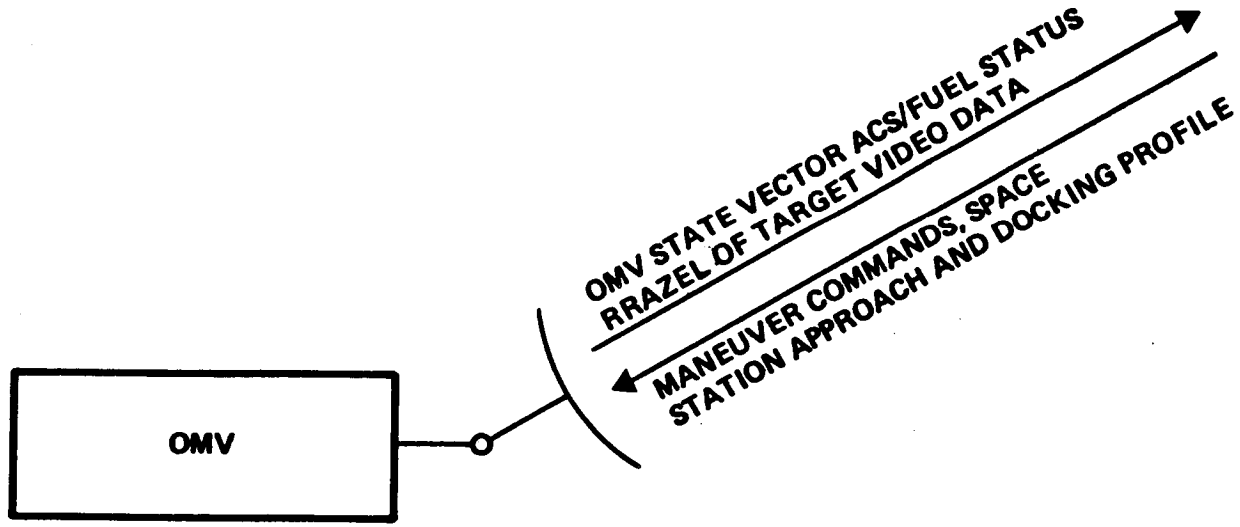
Onboard Video System



Zone One Radar Tracking



OMV External Data Flow



Outline

TRW

- Proximity operations as seen from SSDS viewpoint
- SSDS involvement in proximity operations
- SSDS data management and processing

TRW

Proximity Operations Files, SSDS Data Base

- Flight control procedures for OMV, OTV, Free Flyers, EVA
- Docking procedures for OMV, OTV
- Grappling/tending procedure for MRMS
- Flight rules (relative speed, closest approach etc)
- Restricted zone boundaries and applicability
- Antenna blockage patterns, slew rates, ranges
- Reboost schedule and profile
- Sunrise/sunset, sun vector
- Subsystem test data and configuration
- EVA, MRMS, OMV and OTV operations plans
- Space object ephemeris
- Video Data

INPUT DATA RATES TO SSDS (EXCLUDING VIDEO)

FROM ONBOARD:	BITS/SECOND
RADAR - RETURNS & STATUS	2K
MRMS - LOCATION & STATUS	100
SPACE OBJECT EPHEMERIS	50
COLLISION C&W (OBJECTS BEYOND ZONE 2)	50
RCS STATUS	100
FROM EXTERNAL SOURSES	
SPACECRAFT COMMANDS FROM GROUND	1K
SPACECRAFT GROUND DATA & STATUS (10 OBJECTS)	10K
TOTAL	13.3K

VIDEO INPUT DATA RATES (Mbps) TO SSDS

	COLOR UNCOMPR	COLOR COMPR	BLACK & WHITE UNCOMPR	BLACK & WHITE COMPR
FROM ONBOARD: (3 CHANNELS)	336	75	105	15
FROM EXTERNAL SOURCES:				
OMV (2 CHANNELS)	224	50	70	10
OTV (1 CHANNEL)	112	25	35	5
EVA (1 CHANNEL)	112	25	35	5
GROUND (1 CHANNEL)	112	25	35	5
TOTAL (Mbps)	896	200	280	40

ALL VIDEO IS 30 FRAMES/SECOND

TRW

Output Data Rates FROM SSDS (EXCLUDING VIDEO)

	Bits/Second
• Tracking	
Commands	1K
• Free flyers (incl OMV, COSP, coorbiters)	
Commands	10K
• EVA's	
Commands	1K
Text and graphics	128K
Audio (1 channel)	16K
• Crew displays (3 displays)	300K
• TDRSS downlink	110K
Total	566K

TRW

VIDEO OUTPUT DATA RATES (Mbps) FROM SSDS

	COLOR UNCOMPR	COLOR COMPR	BLACK & WHITE UNCOMPR	BLACK & WHITE COMPR
TDRSS DOWNLINK (3 CHANNELS)	336	75	105	15
ONBOARD INSTANT REPLAY (1 CHANNEL)	112	25	35	5
TOTALS (Mbps)	448	100	140	20

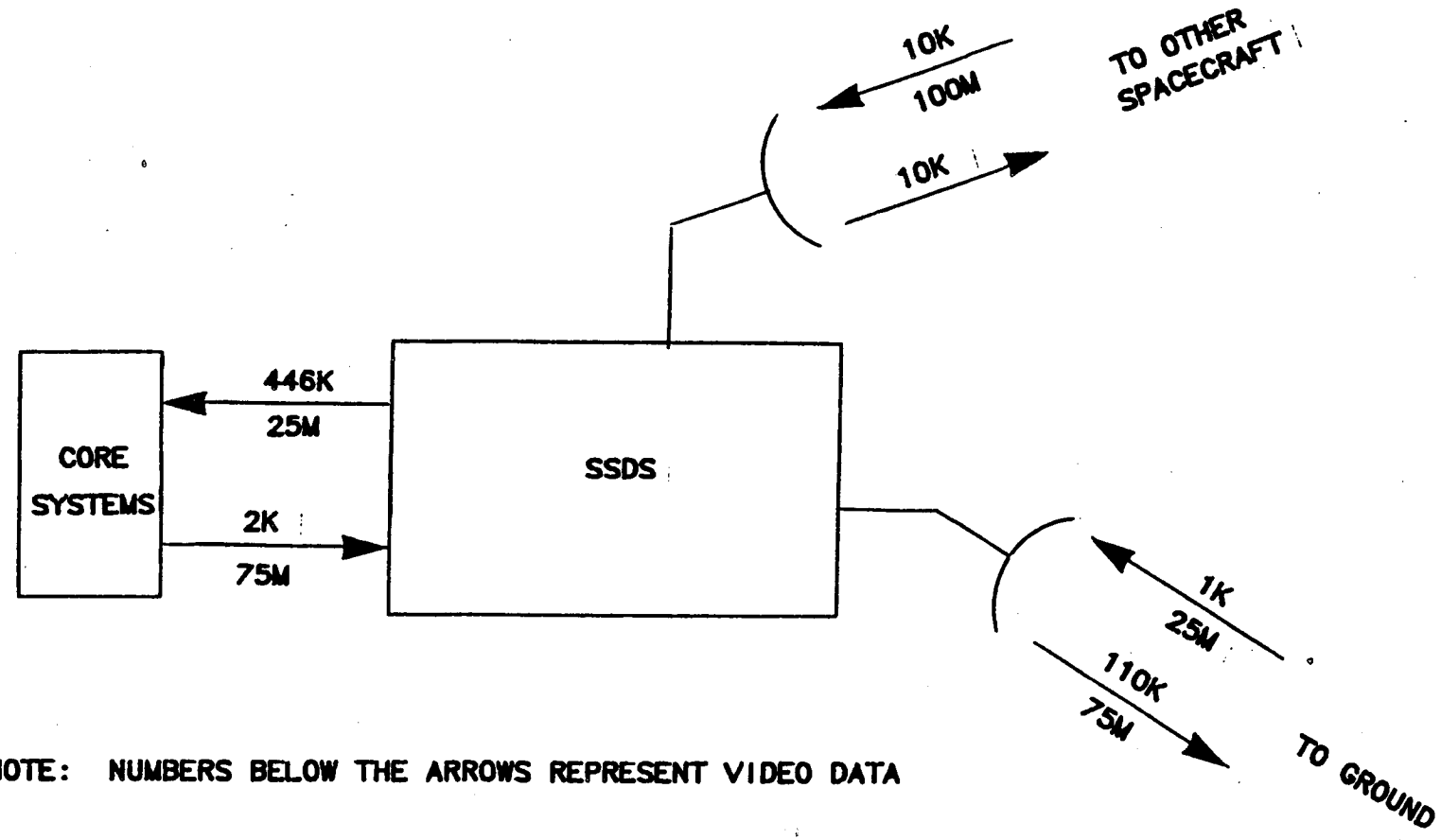
TRW

SSDS Data Processing Requirements for Proximity Operations

NAME	MEAN CPU (ips)	PEAK CPU (ips)	MEM (wd)	MASS STORAGE (wd)**
TRAFFIC CONTROL	5K	50K	60K	5.6G*
TRAFFIC PLANNING	100	10K	5K	10M
GN SUPPORT	10K	300K	15K	8K
TOTALS	60K	375K	80K	5.6G

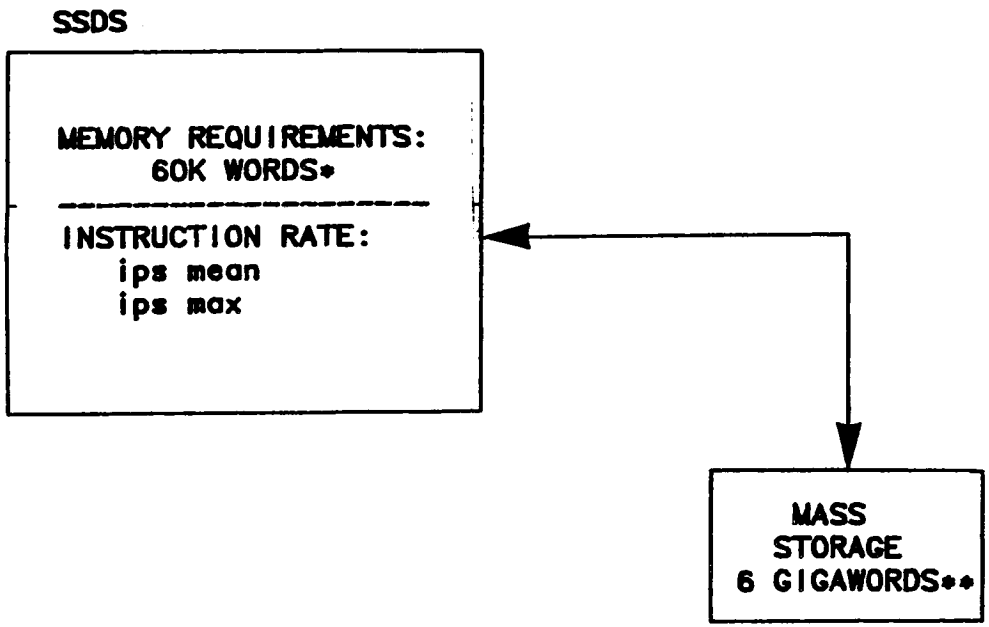
*ONE VIDEO CHANNEL FOR 60 MINUTES

**16 BIT WORDS



NOTE: NUMBERS BELOW THE ARROWS REPRESENT VIDEO DATA

INPUT/OUTPUT DATA RATES, SSDS



*16 BIT WORDS
**ONE VIDEO CHANNEL FOR 60 MINUTES

PROCESSING & STORAGE REQUIREMENTS, SSDS

TRW

CONCLUSIONS

- SSDS CAPABILITIES ARE NOT SERIOUSLY CHALLENGED BY THE REQUIREMENTS OF PROXIMITY-OPERATIONS EXCEPT IN THE AREA OF VIDEO DATA HANDLING.
- SINGLE-CHANNEL VIDEO DATA RATES PRECLUDE INDISCRIMINATE TRANSMISSION AND/OR RECORDING OF VIDEO DATA.
- VIDEO DATA HANDLING TRADEOFFS WILL CONTINUE TO BE ADDRESSED.
  - DATA COMPRESSION VERSUS PICTURE FIDELITY.
  - ONBOARD STORAGE VERSUS TRANSMISSION TO GROUND.
  - ANALOG VERSUS DIGITAL STORAGE.

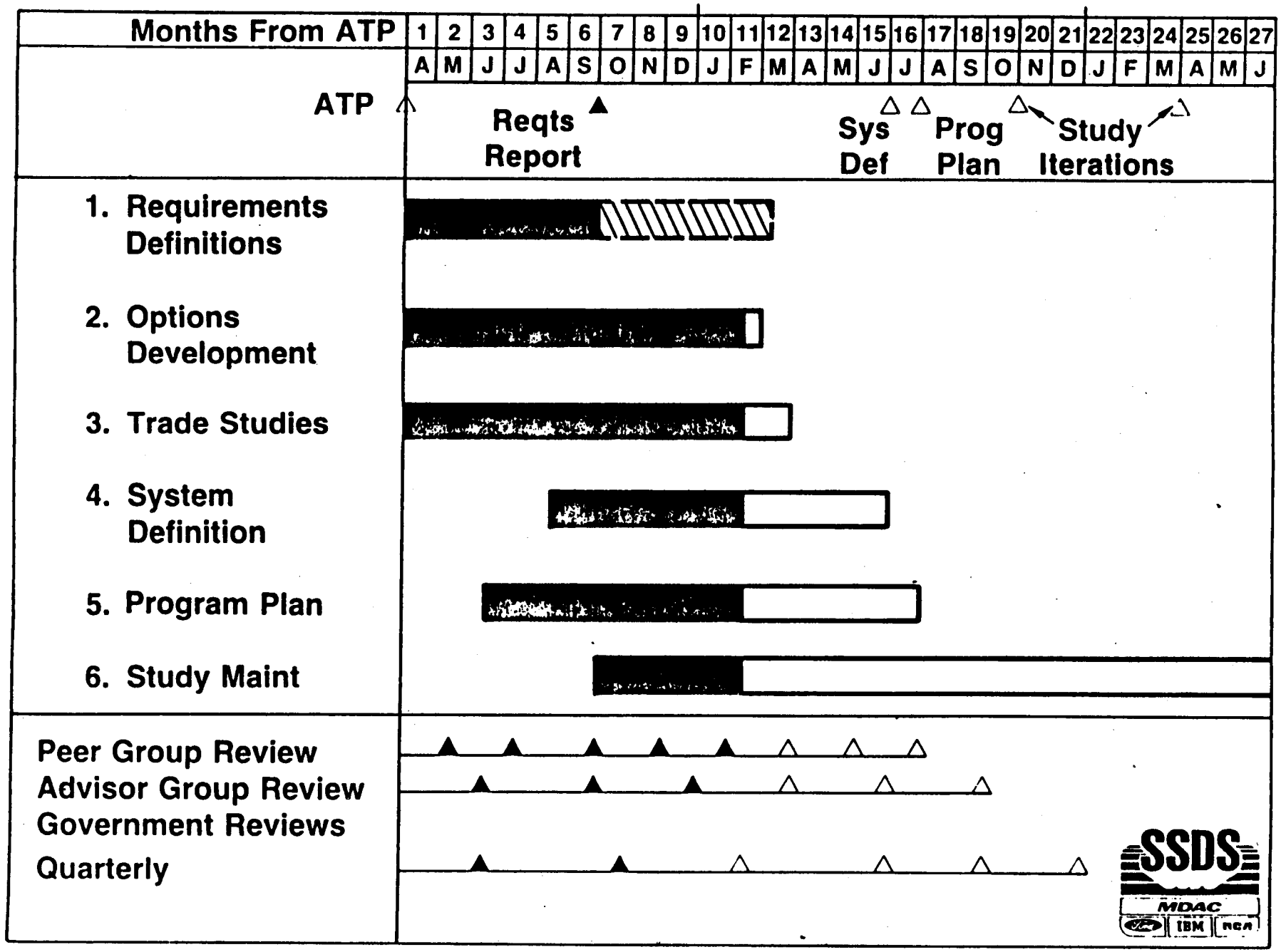
THE EFFECT OF RENDEZVOUS AND PROXIMITY OPERATIONS ON THE SPACE STATION DATA MANAGEMENT SYSTEM ARCHITECTURE

VGZ904

- The Reference DMS Architecture
- Rendezvous/Proximity Operations Ground Rules, Scenarios, and Definitions
- DMS Architecture and Interfaces
- DMS Architecture Issues
- Summary/Conclusions/Recommendations

STUDY SCHEDULE

VGZ340



SSDS MDAC IBM RCA

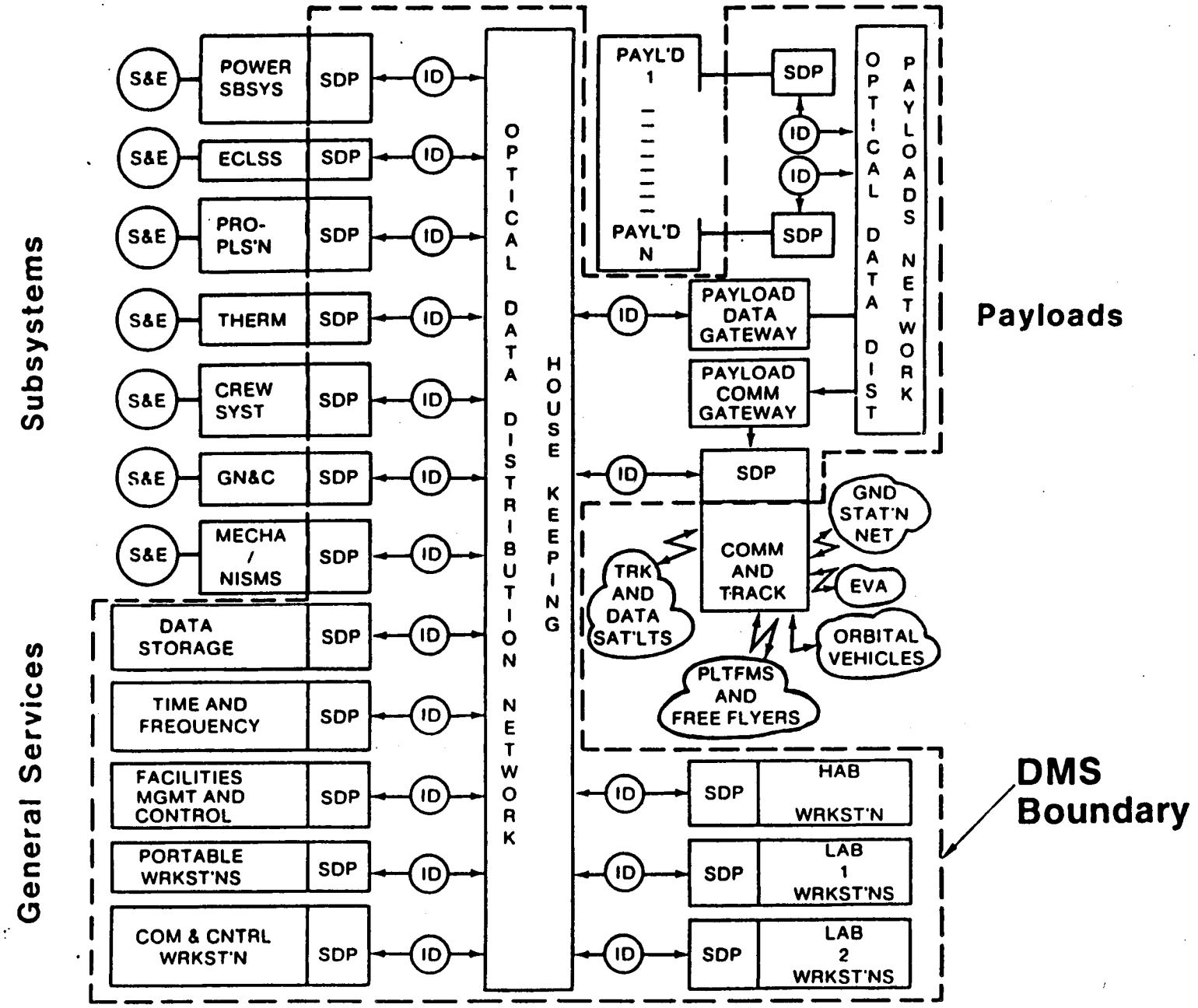
VGZ214

TRADE STUDY STATUS

Trade Studies	Definition Initiated	Definition Complete	Trade Analyses Initiated	Preliminary Presentation
		GSFC Review		
1. Space Automony	X		X	11/84
2. Function Automation	X		X	11/84
3. AI Automation	X	10/84	X	2/85
4. End-To-End Networking	X	12/84	X	2/85
5. Standards/Commonality	X	12/84	X	2/85
6. Onboard Local Area Net.	X	11/84	X	2/85
7. BIU/Transmission Media	X	11/84	X	2/85
8. Distr. Operating Sys.	X			
9. Software Development	X			
10. Fault-Tolerant Computing	X			
11. Space Qual. Computers	X			
12. Distr. Data Base Mgmt.	X			
13. System Int., Test., & Verif.	X			
14. Crew Workstations	X	11/84	X	
15. Languages - Higher Order & Test	X			
16. Mass Storage	X			
17. Space Communications	X			
18. Mission Buildup				
19. Subsystem Contracting				

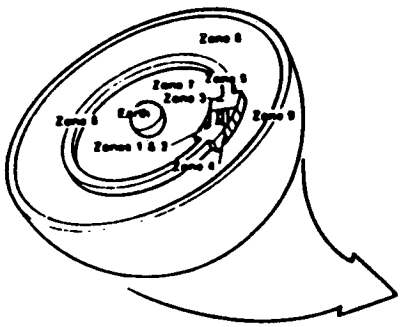
REFERENCE DMS ARCHITECTURE

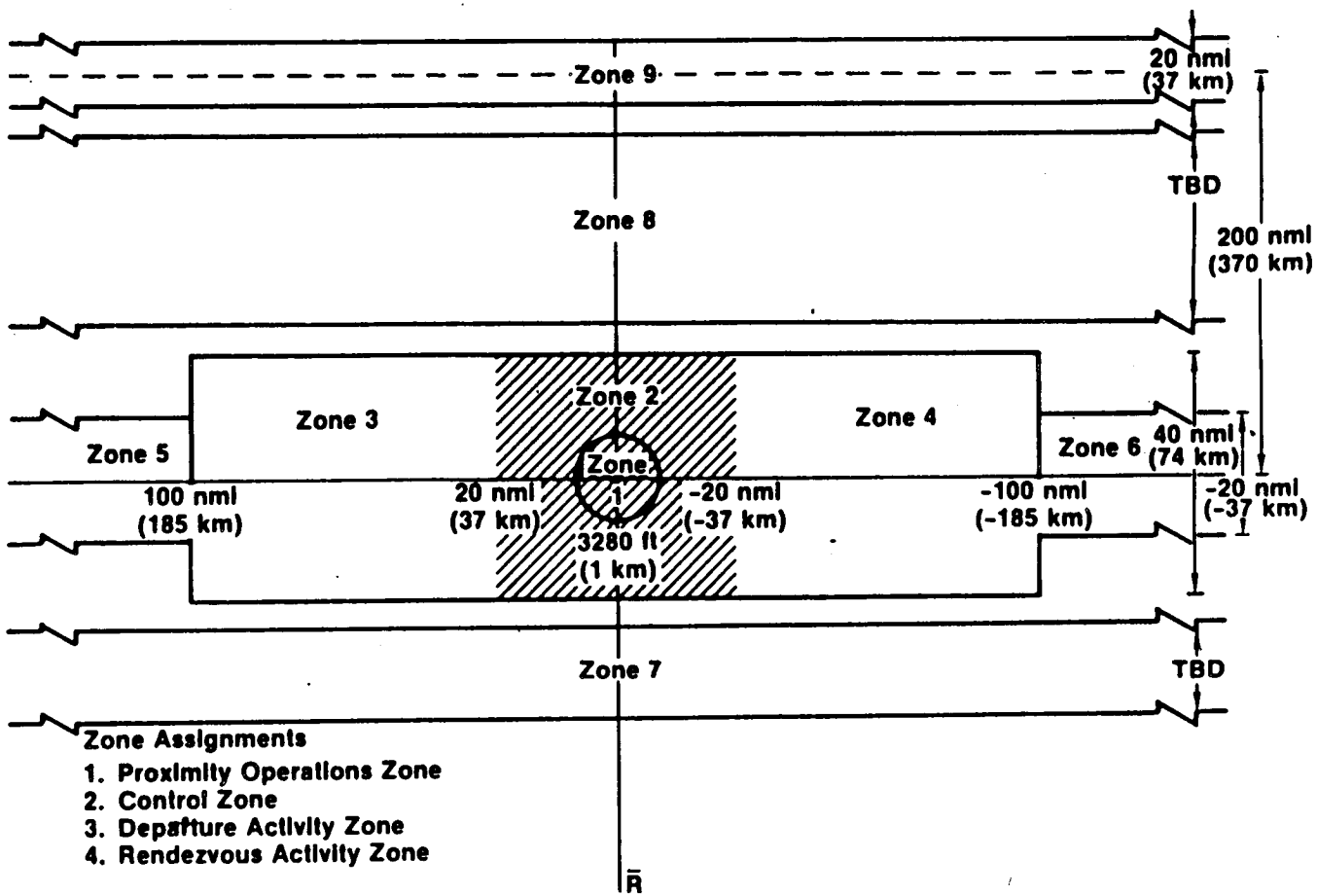
VGZ905



VGZ906

OPERATIONAL CONTROL ZONES





Zone Assignments

1. Proximity Operations Zone
2. Control Zone
3. Departure Activity Zone
4. Rendezvous Activity Zone

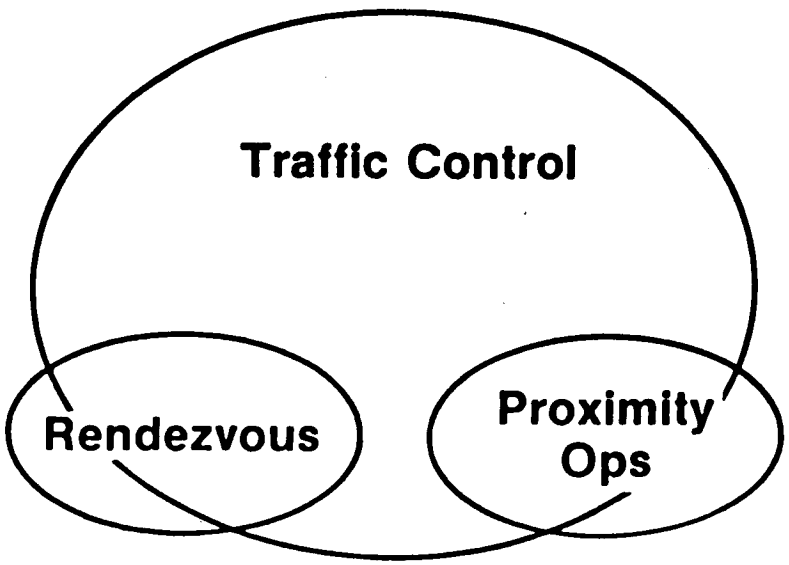
VGZ907

DEFINITIONS

Traffic Control — Tracking, Monitoring, Controlling of Space Systems Operating Within Stations Area of Influence (30° Cone Along ± $\bar{V}$ to a Distance of 2000 km)

Rendezvous — Process or Orbital Trajectory Maneuvering to Bring a Spacecraft to a Specified Point With No Relative Motion

Proximity Operations — Maneuvers Required to Maintain Two or More Spacecraft Within Close Visual Distance or Within Physical Contact With One Another



VGZ909

RENDEZVOUS SCENARIOS

Vehicle	Starting Locations	Rendezvous Location
Orbiter	LEO	SS Rendezvous Zone
Orbiter	LEO	COP Rendezvous Zone
Orbiter	LEO	POP Rendezvous Zone
OMV	LEO	SS Rendezvous Zone
OTV	GEO/HEO	SS Rendezvous Zone
COP	Co-Orbiting Zone	SS Rendezvous Zone
OMV	Orbiter (LEO)	POP Rendezvous Zone
OMV	SS Departure Zone	COP Rendezvous Zone
OMV	SS Departure Zone	Free-Flyer Orbit
OTV	SS Departure Zone	GEO/HEO

Note: Highlighted Items Are Ones With Primary Effect on DMSS Architecture

PROXIMITY OPERATIONS SCENARIOS

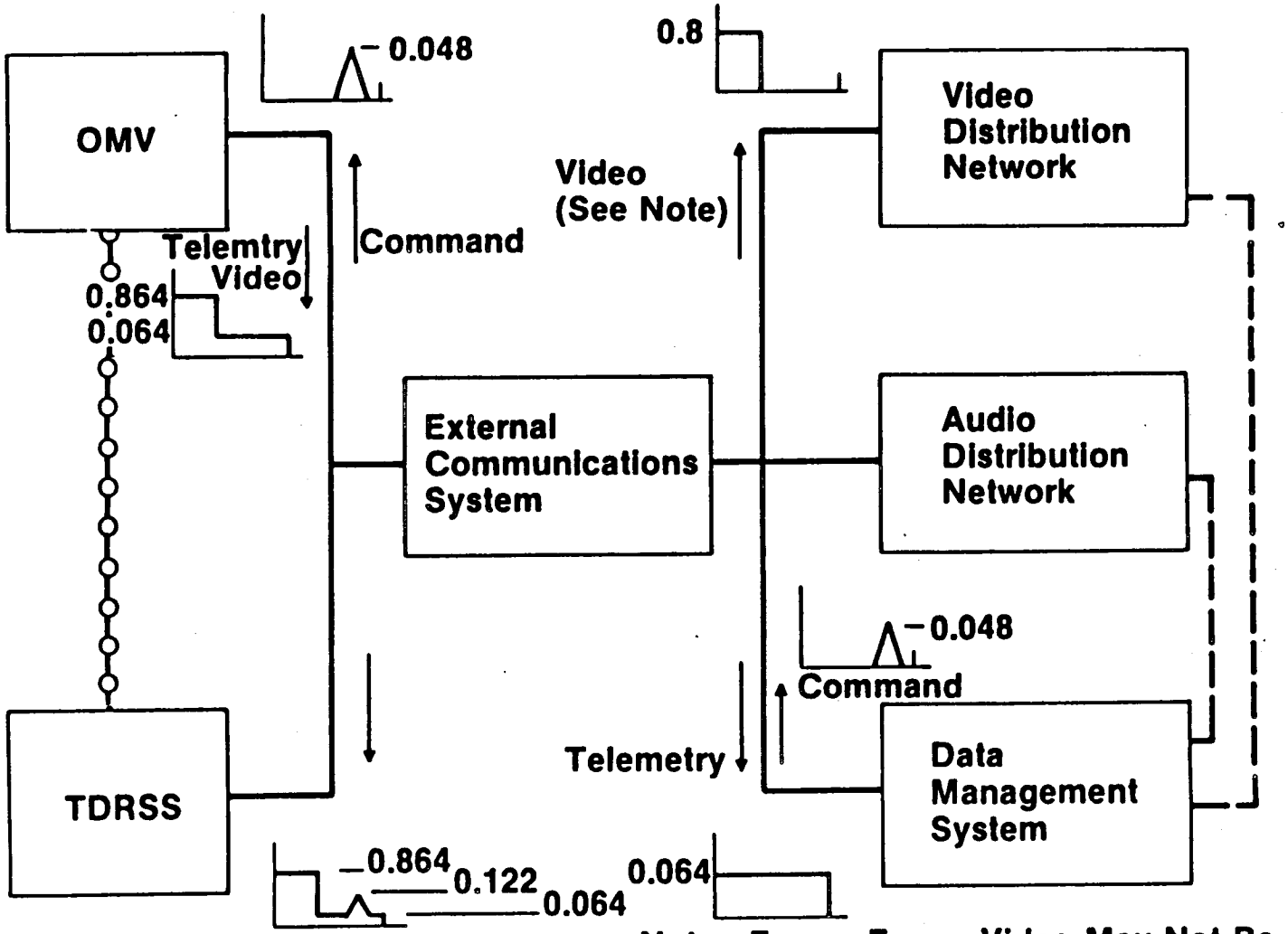
VGZ908

Active Vehicle	Passive Vehicle	Control Location
OMV/OTV	SS	SS
OMV/OTV	COP	SS or Ground
OMV/OTV	POP	Ground or Orbiter
OMV	Free-Flyer	SS, Ground, or Orbiter
OMV	Orbiter	Orbiter
STS	SS	STS
STS	COP OR POP	STS
COP	SS	SS
FF	SS	SS
MMU	SS	MMU

Note: Highlighted Items Are Ones With Primary Effect on DMS Architecture

VGZ456

OMV SCENARIO



Note: Freeze Frame Video May Not Be Adequate for Interactive Robotic Interface

VGZ457

OMV SCENARIO

Years After IOC	0	1	2	3	4	5	6	7	8	9	10
OMV Events Per Year*		12	16	16	15	3	10	2	27	29	27
OMV Hrs Per Year**		96	128	128	120	24	80	16	216	232	216

11-43

Alternate Link

Space Station Required to: 100 nmi

Source: RFP p. C-4-36

Source Documents for TV

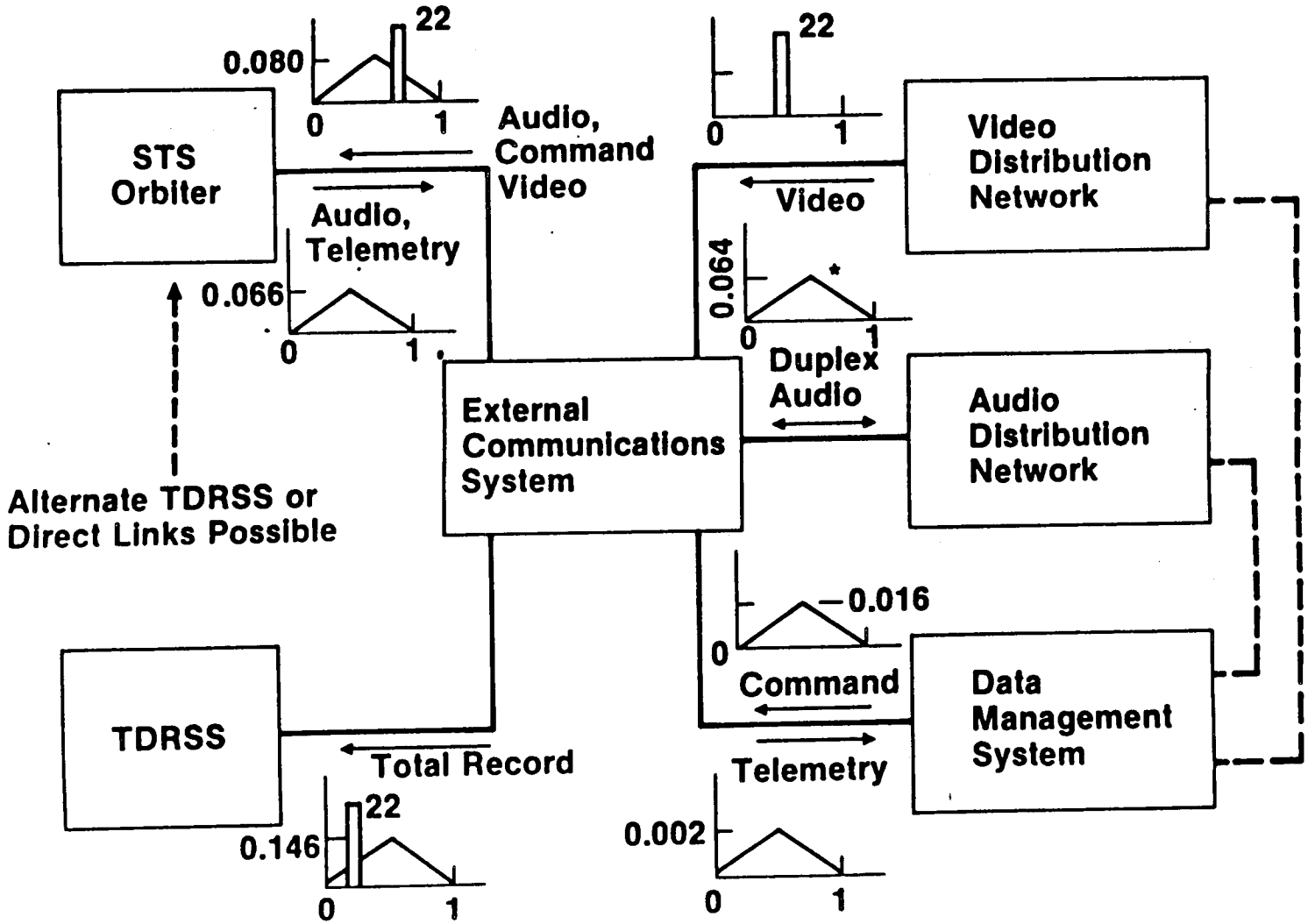
1. OMV SOW, Jan 1984
2. RFI to RCA for OMV TV Cameras

*p. C-2-21, RFP

**Estimated at 8 Hrs Per Event

ORBITER DOCKING/UNDOCKING SCENARIO

VGZ454



* — 2 Voice Channels to Orbiter

VGZ455

ORBITER VISITS (YEARLY) SCENARIO

Years After IOC	0	1	2	3	4	5	6	7	8	9	10
Orbiter Dockings Per Year*		4	4	8	8	8	8	12	12	12	12
Other Mission-Oriented Dockings**		6	5	8	7	7	10	10	16	14	11
Total Per Year (Est)		10	9	16	15	15	18	22	28	26	23

*Based on Rotating 6 Crew Members Per Orbiter Flight and a 90-Day Tour of Duty

**Based on an Early Mission Model

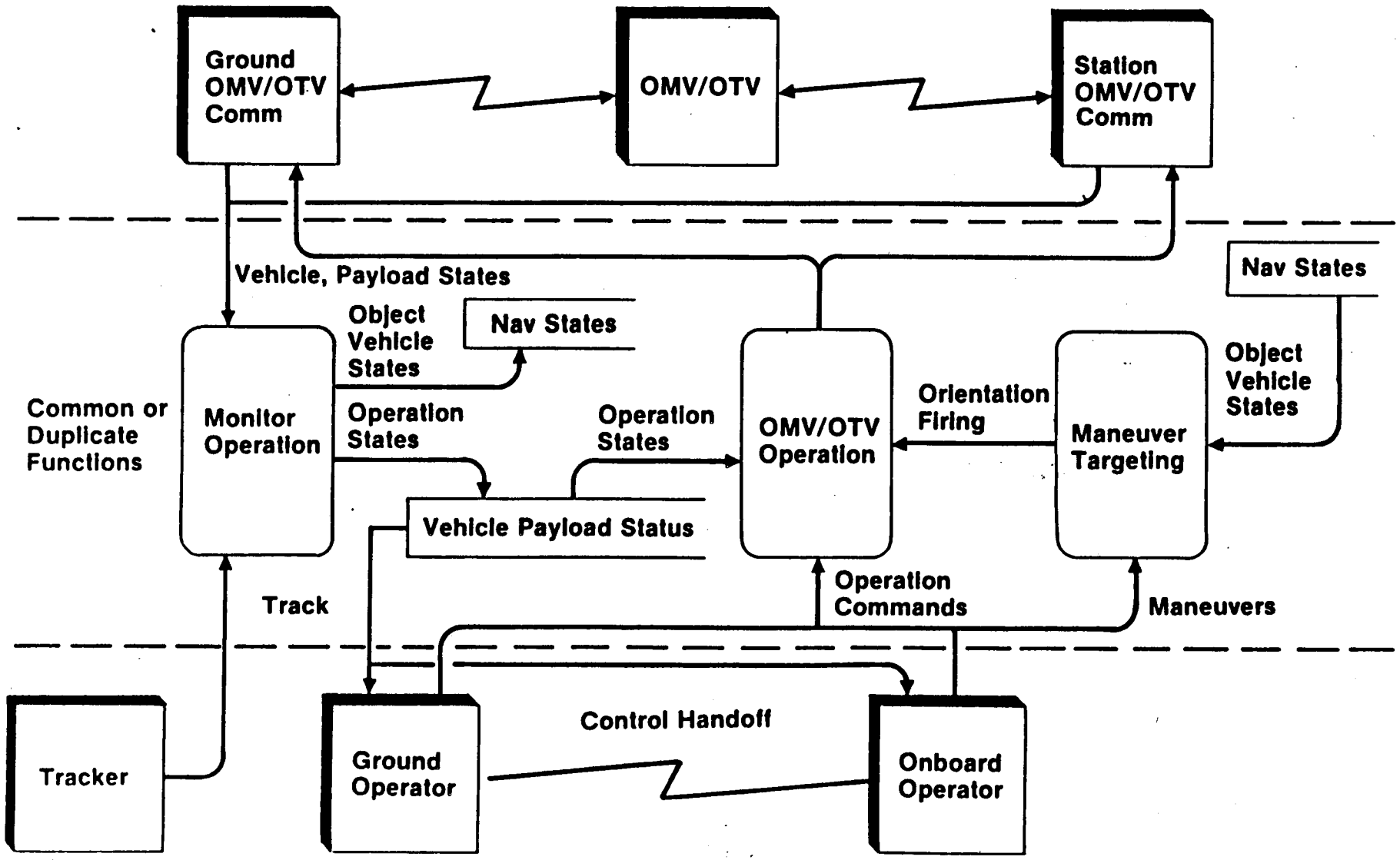
GROUND RULES AND ASSUMPTIONS

VGZ910

- Operations Planning Is Done on Ground Initially
- Design Goal Is for 1-Man Control of Real-Time Proximity Operations
  - Man-In-Loop (IOC)
  - Supervised Automatic Operations (Growth)
- OMV Operations May Be Controlled from SS Out to Communications LOS Limit (2,000 km)
- Capability to Train the Onboard Operator for Proximity Operations Is Required
- EVA Is Considered Only to the Extent That It Is in Concert with Proximity Operations
- Tethered Payloads Must Be Considered in Traffic Control

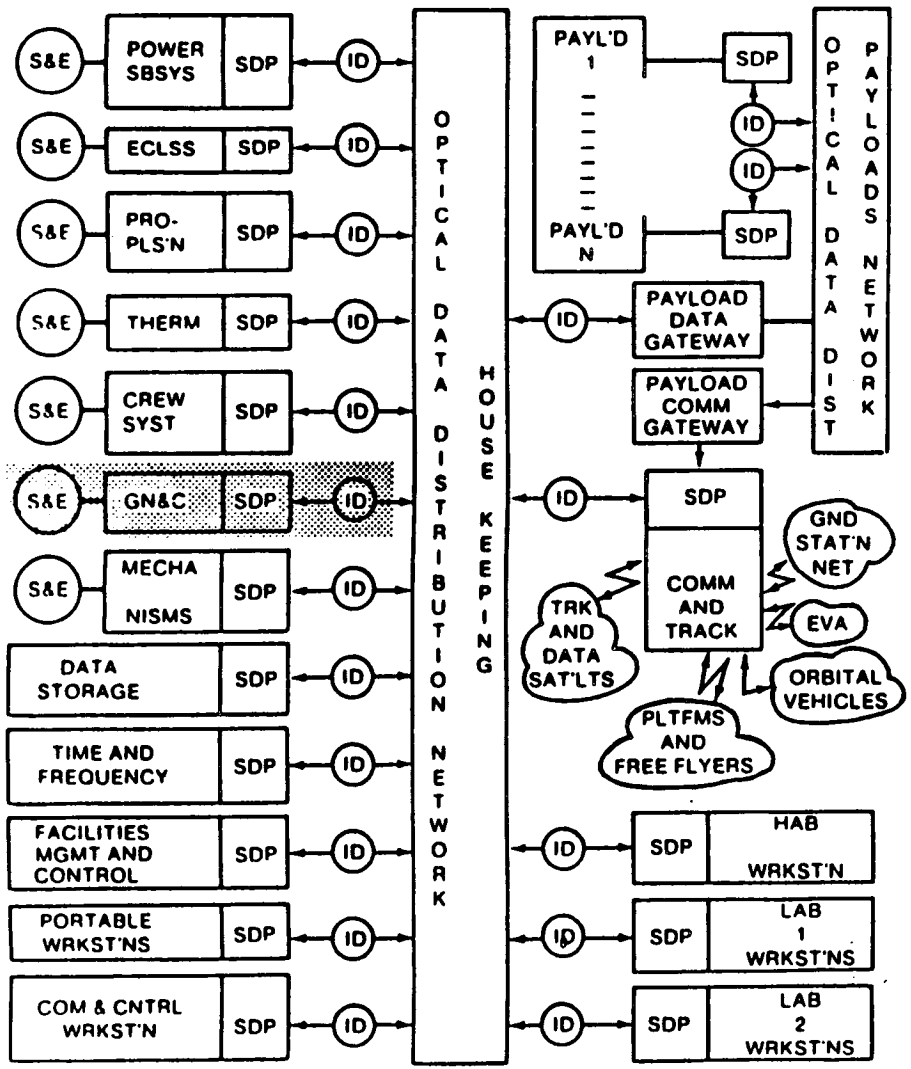
OMV AND OTV RENDEZVOUS AND DEPLOYMENT MAY BE CONTROLLED FROM THE SPACE STATION OR SSOCC

VGZ911



VGZ912

GN&C INTERFACE



Functions Allocated to GN&C

- Traffic Control (Including Rendezvous)
- Proximity Operations Management
- Station Safety (Collision Avoidance)
- Attitude Sensor Data Processing

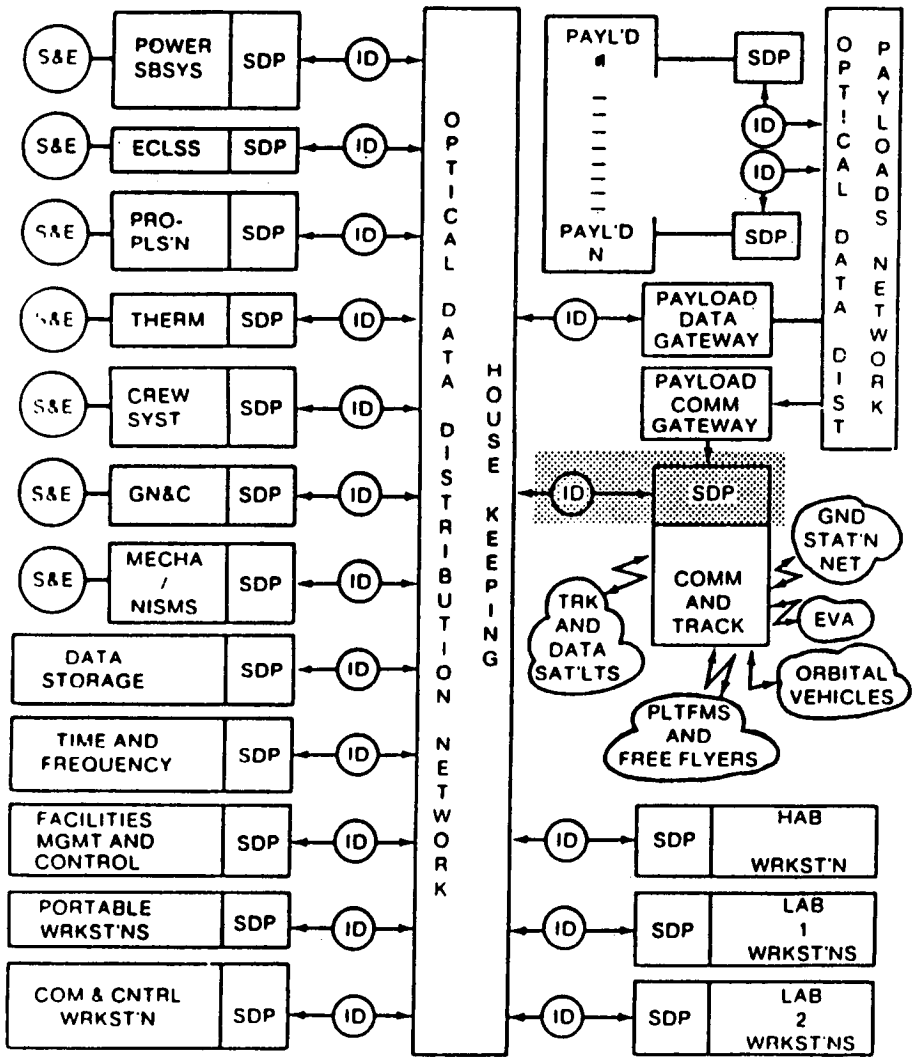
Functions Allocated to DMS

- Onboard Data Distribution
- Caution and Warning
- Command Management
- Display Generation
- Data Base Management

11-48

VGZ913

C&T INTERFACE



Functions Allocated to C&T

- Target Vehicle Communications
- Target Vehicle Tracking, Including Sensor Signal Processing
- Television Processing and Display
- Audio Processing and Distribution
- GPS Signal Reception and Processing

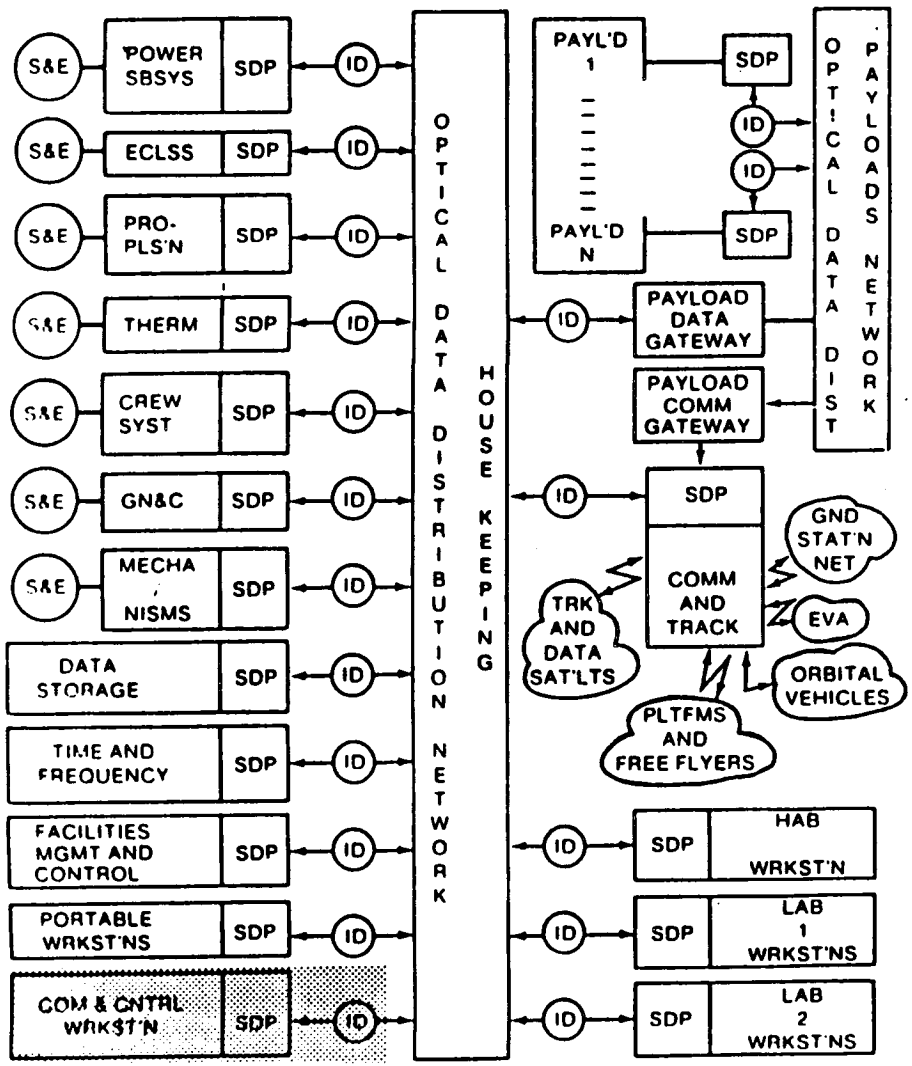
Functions Allocated to DMS

- Onboard Data Distribution
- Caution and Warning
- Command Management
- Display Generation
- Data Base Management

11-49

VGZ914

OPERATOR INTERFACE



Functions Allocated to Operator

- Real-Time Command and Control
- System Supervision
- Planning and Scheduling
- Redundancy Management Override
- Program/Data Base Modification

Functions Allocated to DMS

- Command Management
- System Status Monitor
- Display Generation
- Caution and Warning
- Simulation and Training Support
- Real-Time Command and Control (Growth)

THE VIRTUAL IMAGE TAKEOFF AND LANDING (VITAL) SYSTEM PROVIDES DISPLAY CAPABILITIES THAT SUPPORT PROXIMITY OPS SIMULATIONS

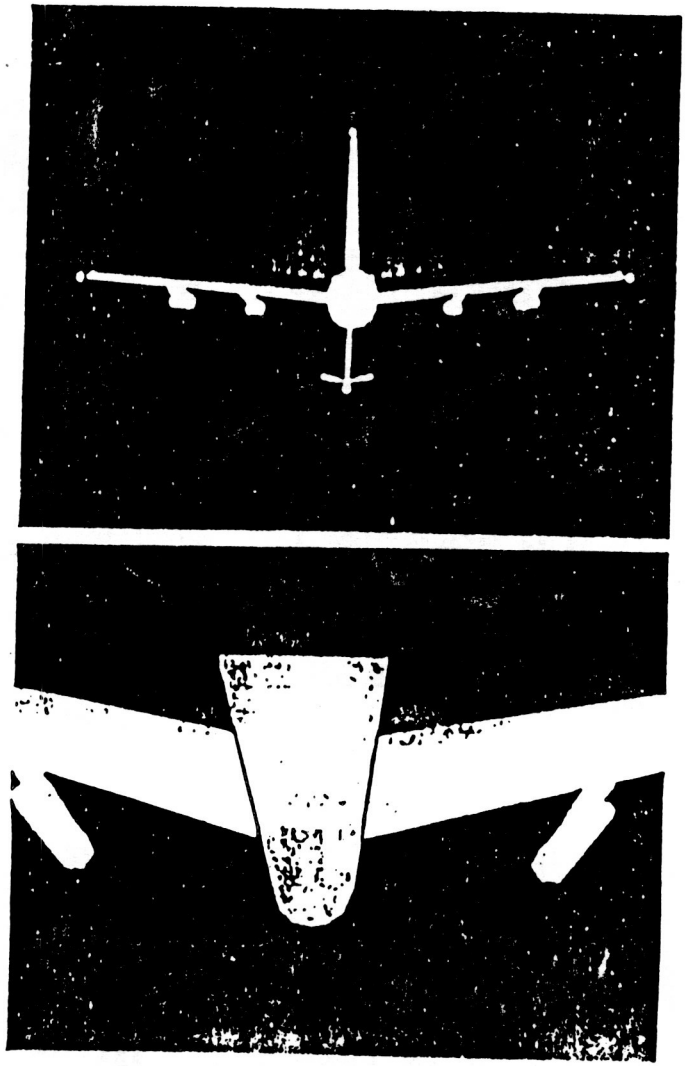
VGZ915

Vital Features:

- Realistic, Computer-Controlled Scenes
- Full-Color
- Projected "3-D" Scenes
- User Creation of Scenes
- Proven Architecture
- Extensive Applicaiton Experience

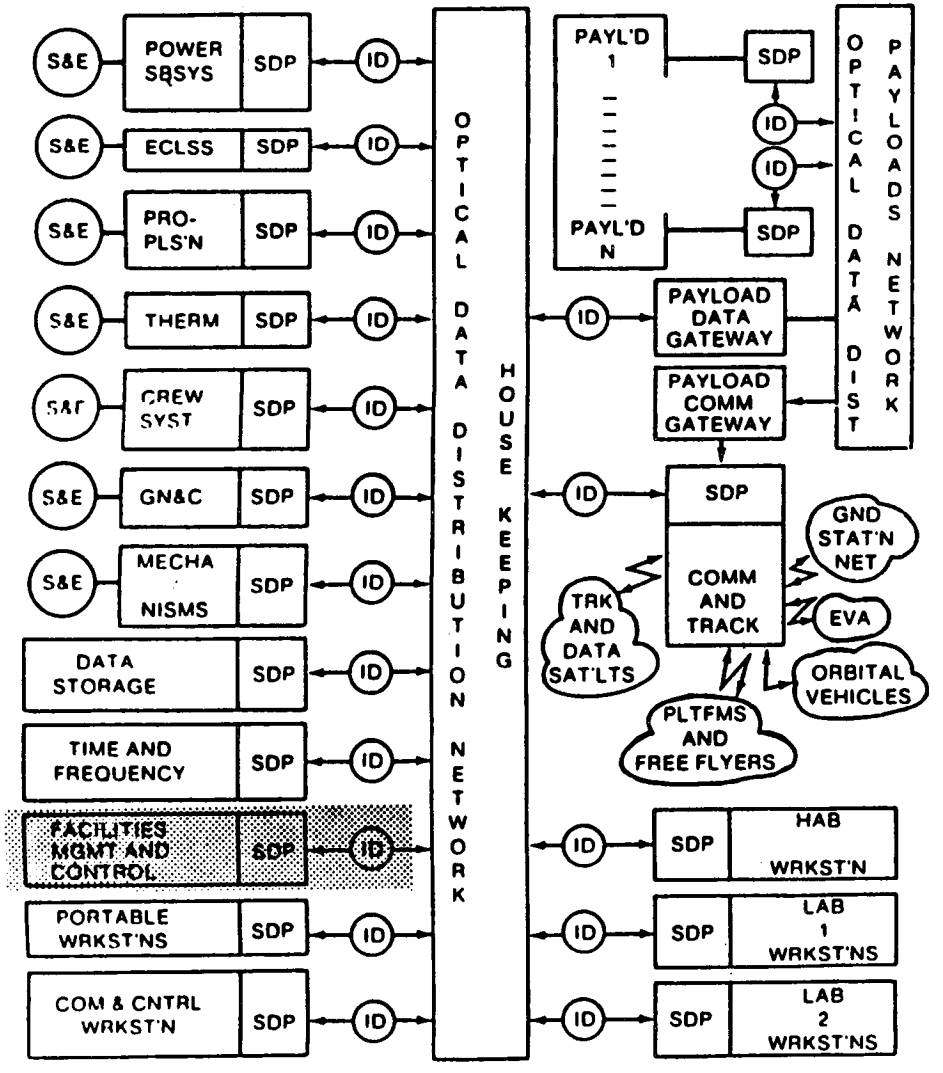
Proximity Ops Applications

- Simulate "Out-the-Window" Scene
- Simulate TV Images
- Ground Training
- Onboard Training



VGZ916

FACILITY MANAGEMENT AND CONTROL

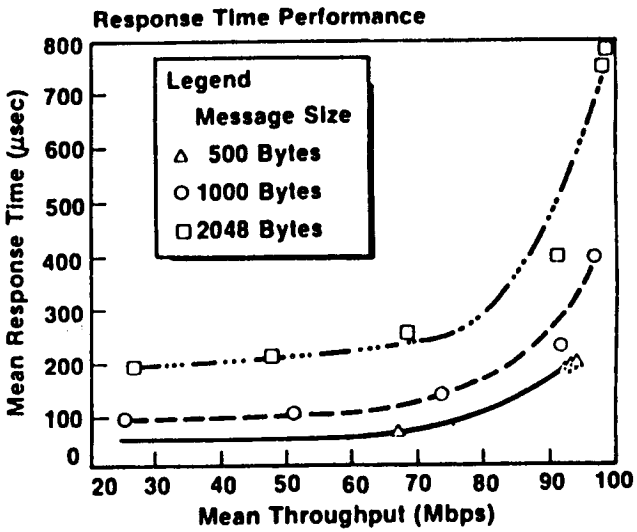


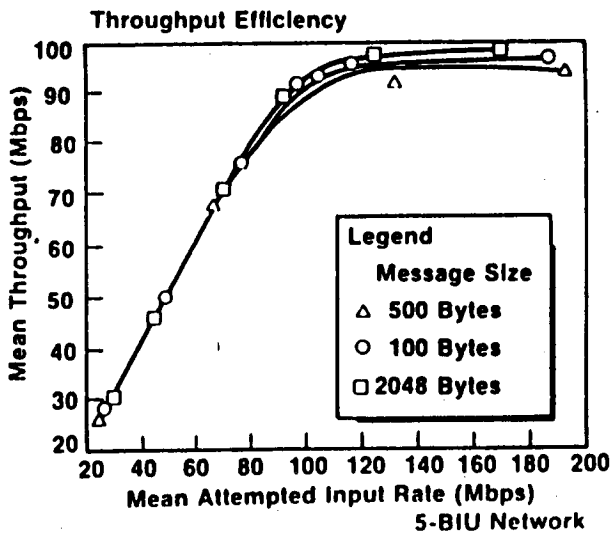
- Planning and Scheduling Support
- Resource Allocation
- Command Management
- System Status Monitor
- Caution and Warning
- Simulation and Training Support
- Maintenance Procedures and Management

DATA NETWORK CONCEPT AND PROTOCOL ARE IMPORTANT FACTORS IN DMS ARCHITECTURE

VGZ918

- High Rate Inter-System Data Traffic Expected
- Message Delay Time Is Important Parameter
- Non-Deterministic (e.g., CSMA/CD) Protocols Probably Not Best Choice
- Simulations and Test Beds Are Important Design Tools





SIZING ESTIMATES OF PROXIMITY OPERATIONS/RENDEZVOUS PROCESSING

NTST Existing Software	Rates	Memory Core
■ Onboard (AP101)		
• Attitude Processing	8-10 sec (Performed in Time Remaining After All Else Processed)	1500 – 1/2 Words
• Orbit Targeting		4000 (Full 32-Bit Word)
• Rendezvous Navigation		
– Measurement Processing	372 msec Every Other Nav Cycle (1 Cycle = 3.84 Sec)	6000
– No Measurement Processing	139.5 msec Every Nav Cycle	75000
Space Station		
• Traffic Control		
• Relative State Nav	2/sec	25K (16-Bit Word)
• Guidance/Targeting	2/sec	20K
■ Proximity Operations	1/sec	15K
■ Attitude Processing (Station)		
• High Rate	10/sec	5K
• Low Rate	.5/sec	10K
■ Track Sensor Data Processing	2/sec	30K
■ Displays	.5/sec	25K

*Estimates Based on Typical Traffic Complement

VGZ919

DMS ARCHITECTURE ISSUES

- Distributed Processing Approach Versus Need for Tightly-Coupled Real-Time Operations
- Need for Reconfigurability and Expandability to Support Increased Traffic, New Operating Scenarios, New Sensors, Increased Automation
- Man-Machine Interface for Maximum Operator Productivity
- Need for a Flexible Priority Scheme

VGZ920

SUMMARY/CONCLUSIONS/ RECOMMENDATIONS

- The Reference DMS Architecture Has the Basic Features Needed for Rendezvous and Proximity Operations

- DMS Architecture Effects Will Be in These Areas:
  - Tight Coupling of Distributed Processes Will Affect Network OS, Resource Allocation (Priority) Function
  - Controls and Displays Concepts
  - Simulation/Training Support

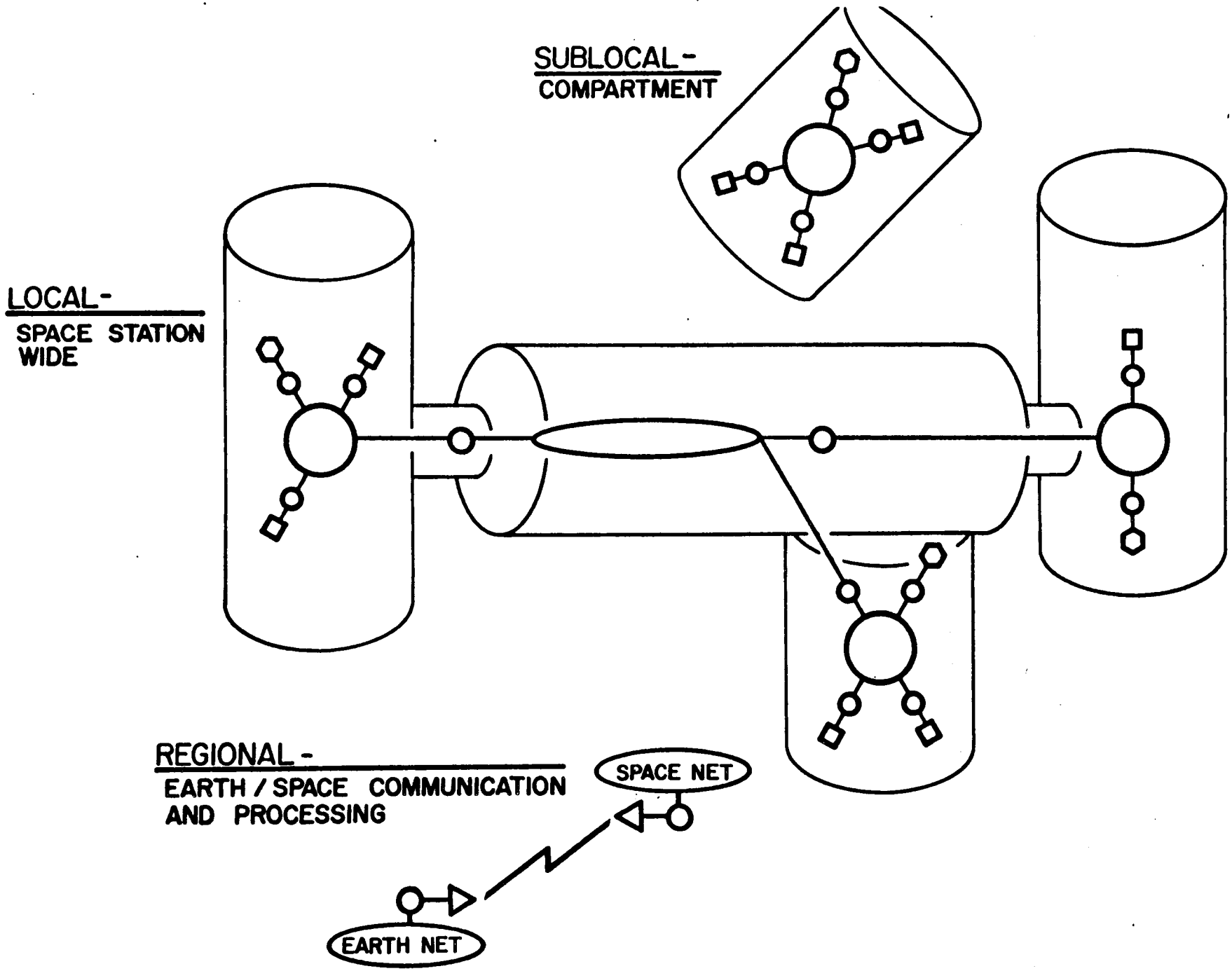
HIGH PERFORMANCE NETWORKS FOR COMBINED VIDEO, VOICE AND DATA

NICHOLAS D. MURRAY, HERBERT D. HENDRICKS, AND EDWIN C. FOUDRIAT
NASA LANGLEY RESEARCH CENTER
HAMPTON, VA

RENDEZVOUS AND PROXIMITY OPERATIONS WORKSHOP

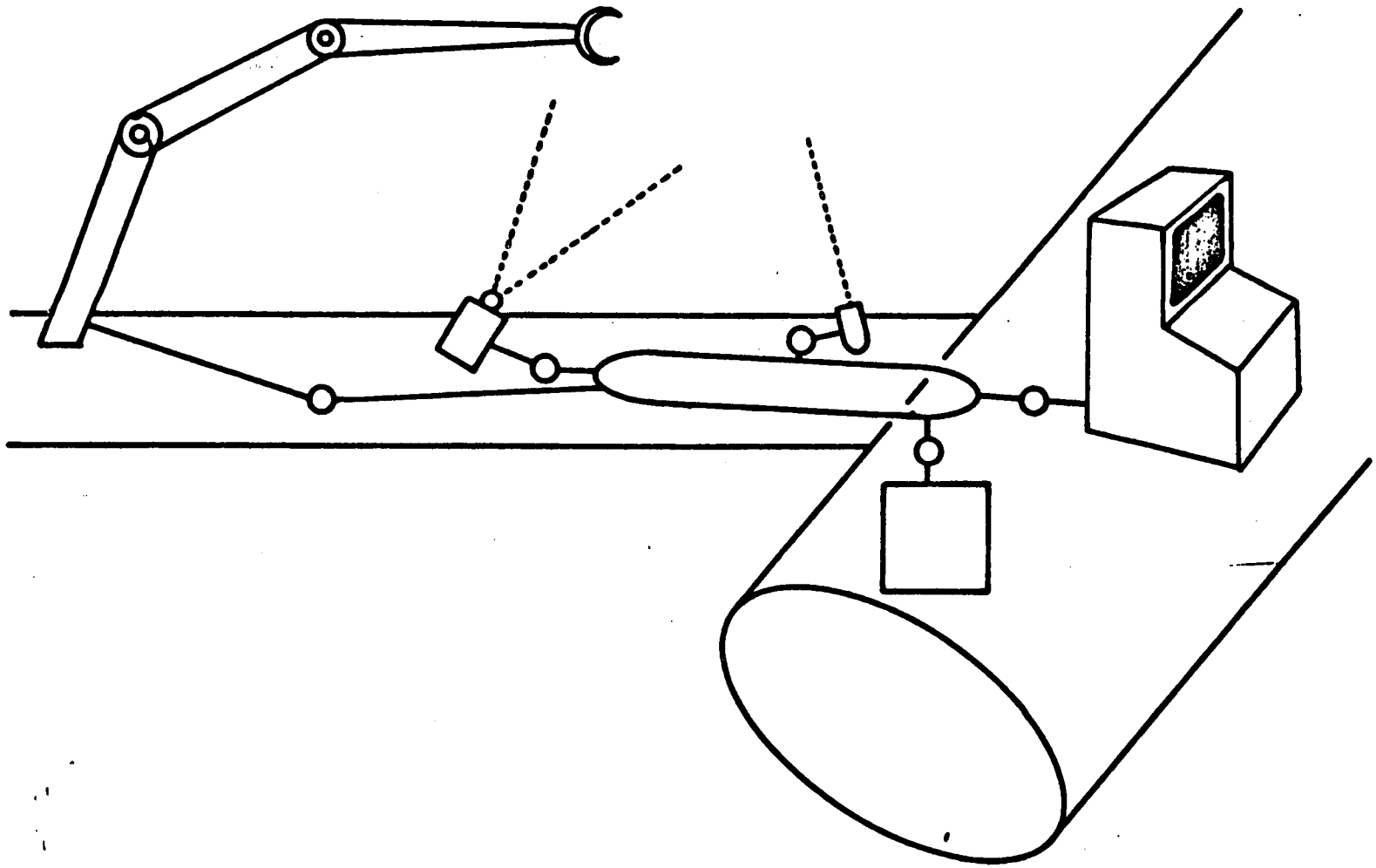
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LYNDON B. JOHNSON SPACE CENTER
FEBRUARY 19-22, 1985

11-57



[A HIERARCHY OF NETWORKS FOR SPACE STATION]

NASA
L-83-10,379



EXAMPLE NETWORK SUPPORTED APPLICATION

MANNED SPACE STATION

REQUIREMENTS FOR INFORMATION PROCESSING	CRITICALITY	PERFORMANCE
1. EXPERIMENTS AND MANUFACTURING	HIGH	MODERATE
2. OBSERVATIONS	HIGH	HIGH
o EARTH o NEAR EARTH o SOLAR SYSTEM o DEEP SPACE		
3. COMMUNICATIONS	HIGH	MODERATE
4. CONSTRUCTION	HIGHER	HIGH
5. STABILITY AND CONTROL	HIGHEST	MODERATE
6. AUTONOMY/AUTOMAINTENANCE	HIGHEST	MODERATE
7. HOUSEKEEPING	HIGHEST	MODERATE

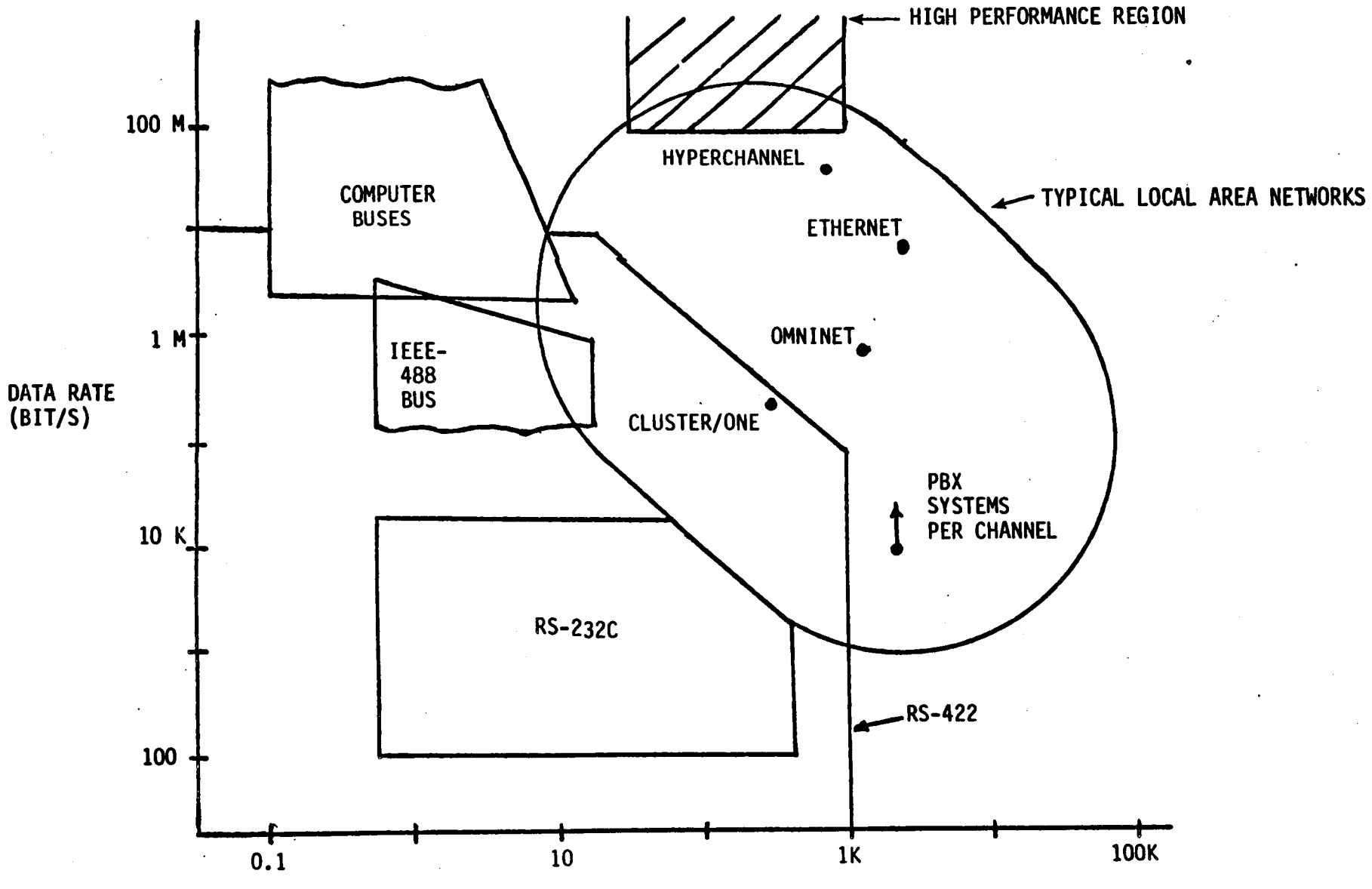
CRITICALITY - HIGHEST IMPLIES MAN RATED OR SPACECRAFT RATED SAFETY.
HIGH IMPLIES HIGH COST BUT NOT SAFETY RELATED.

PERFORMANCE - COMMUNICATION
- MODERATE ~ 50 MBPS
- HIGH > 100 MBPS

PROCESSING
- MODERATE ~ 10 MOPS
- HIGH > 50 MOPS

SUMMARY CHARACTERISTICS OF DATA TRAFFIC SOURCES

TRAFFIC TYPE	NDM. MESSAGE LENGTH (BITS)	RATE BPS	CALL GEN. RATE	HOLDING TIME	DELAY REQUIRE.
STREAM VOICE	CONTINUOUS	64K	LOW	LONG	ALMOST INSTANTANEOUS
STREAM DATA	CONTINUOUS	64K	LOW	LONG	VARIABLE
INTERACTIVE DATA	HUNDREDS TO THOUSANDS	64K	HIGH	SHORT	FRACTION SEC. TO SECONDS
INQUIRY/ RESPONSE DATA	HUNDREDS TO THOUSANDS	64K	LOW	SHORT	SECONDS TO MINUTES
DATA BASE UPDATE	HUNDREDS	TBD	LOW	SHORT	SECONDS TO MINUTES
BULK DATE TRANSFER	GREATER THAN 10^4	TBD	LOW	MED TO LONG	SECONDS TO HOURS
DIGITAL VIDEO	CONTINUOUS	100M	LOW	LONG	ALMOST INSTANTANEOUS


HIGH PERFORMANCE REGION
TYPICAL LOCAL AREA NETWORKS
HYPERCHANNEL
ETHERNET
OMNINET
CLUSTER/ONE
PBX
SYSTEMS
PER CHANNEL
COMPUTER
BUSES
IEEE-
488
BUS
RS-232C
RS-422
100 M
1 M
10 K
100
DATA RATE
(BIT/S)
0.1
10
1K
100K
DISTANCE (M)

INFORMATION NETWORKS

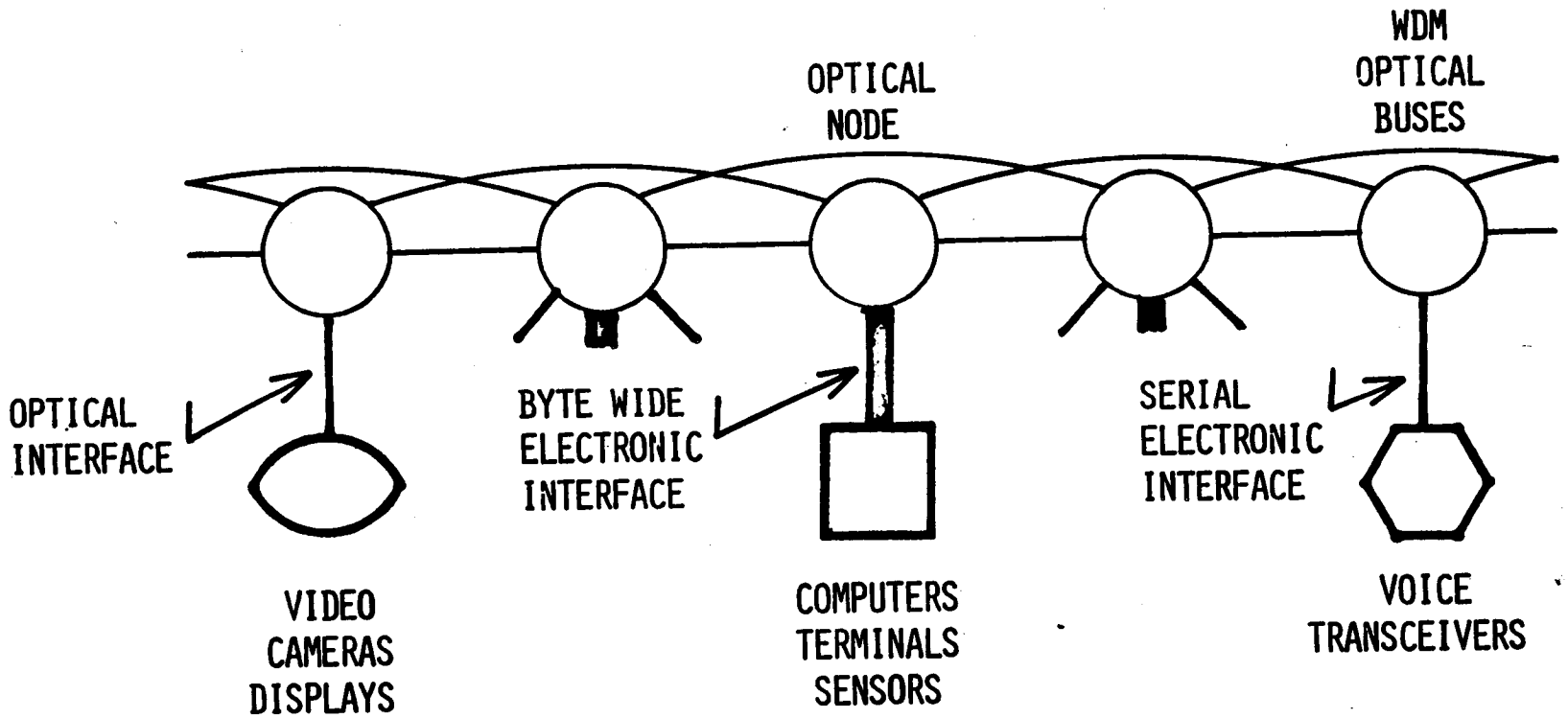
- INTEGRATED - DATA, VOICE, VIDEO
- KEY ISSUES OF NETWORKS
  - INFORMATION FLOW/OPERATING SYSTEM
  - SELF-CORRECTING AND REPAIRING/FAULT TOLERANCE
  - HIGH PERFORMANCE

INFORMATION FLOW BETWEEN COMPUTERS AND OTHER DEVICES REQUIRES A SYSTEM AND ARCHITECTURAL SOLUTION THAT AFFECTS BOTH HARDWARE AND SOFTWARE. CURRENT SYSTEMS USE EXTENSIVE SOFTWARE FOR THE INFORMATION FLOW RESULTING IN A SOFTWARE BOTTLENECK; CONTROL ALGORITHMS AND METHODS FOR TIGHTLY COUPLED, HIGH PERFORMANCE, DISTRIBUTED PROCESSING ARE INADEQUATE; SELF CORRECTING AND REPAIRING TECHNIQUES ARE NOT BEING FULLY APPLIED TO TODAY'S SYSTEMS. REAL-TIME, FULL MOTION, DIGITAL COLOR VIDEO REQUIRES DATA RATES IN EXCESS OF 100 MBPS.

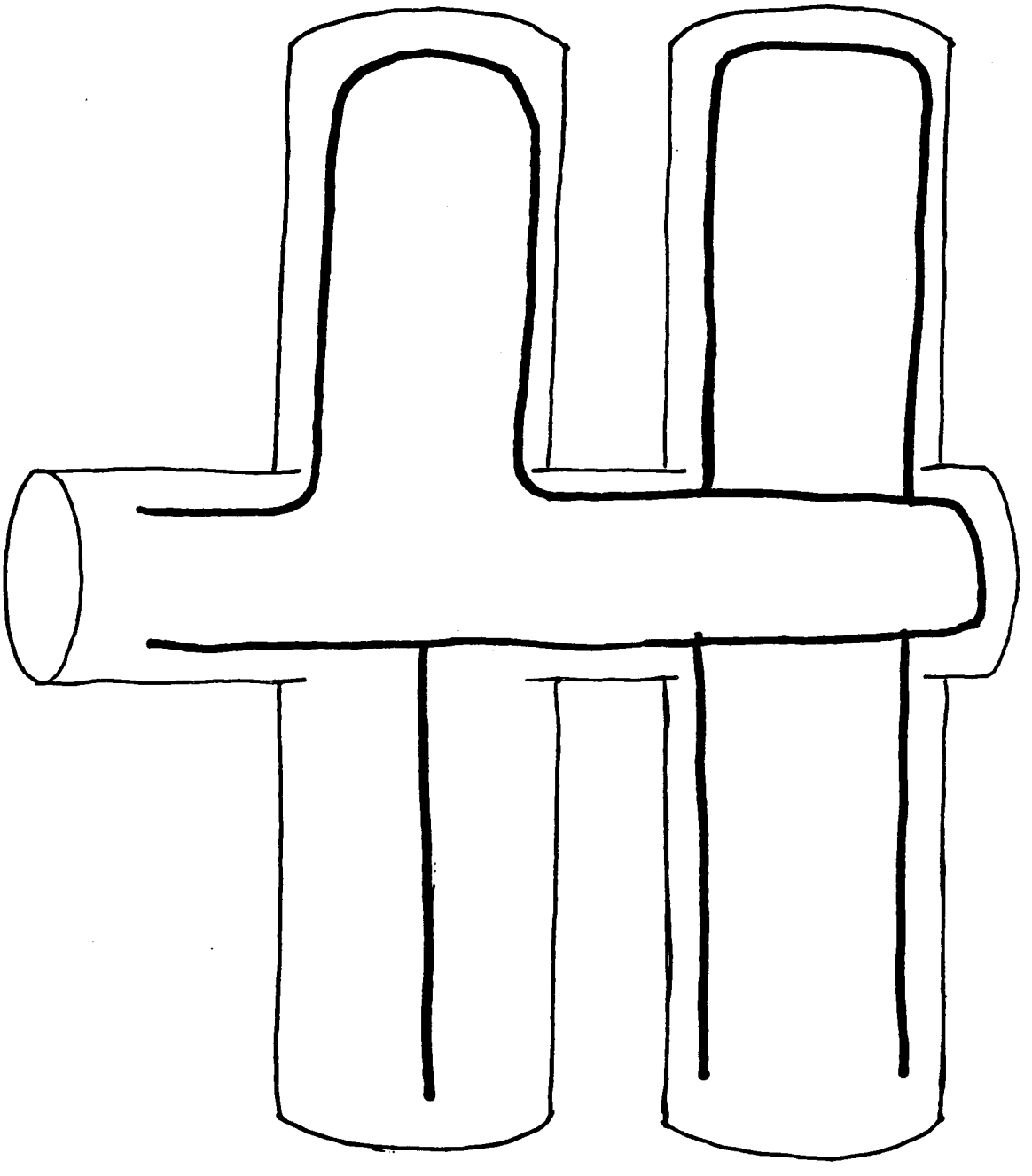
NETWORK TECHNOLOGY THRUSTS

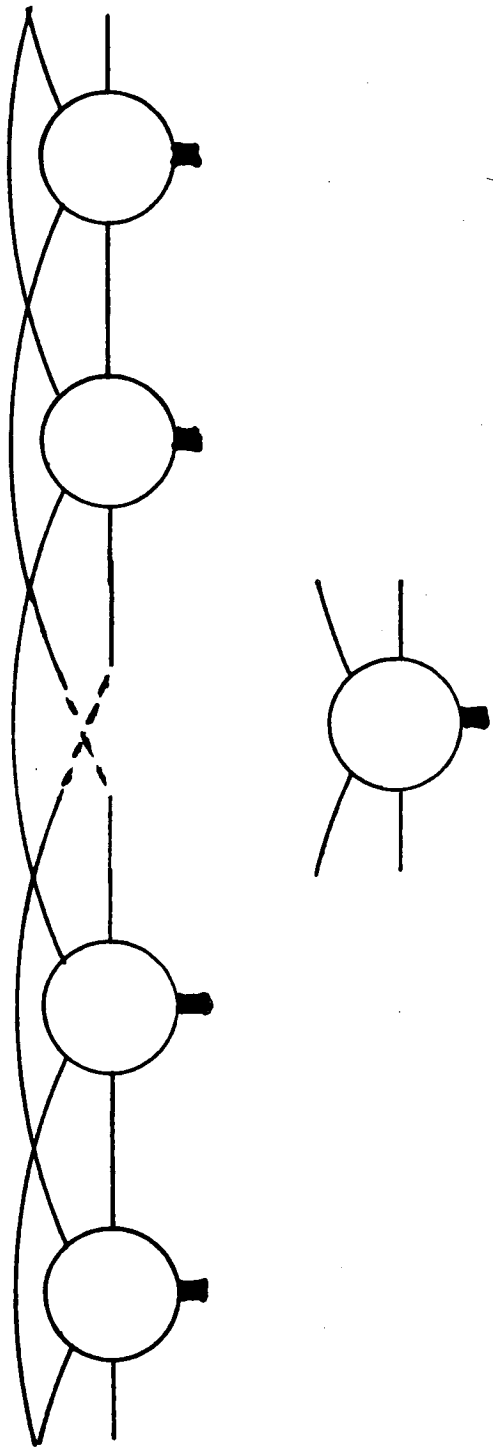
- ARCHITECTURE/TOPOLOGY
- FIBER OPTICS/WAVELENGTH DIVISION MULTIPLEXING
  - LASER SOURCES
  - DETECTORS
  - DEMULTIPLEXERS
  - OPTICAL TRANSMITTER/RECEIVER
- OPTICAL NODE
  - OPTICAL SWITCHING
  - - COUPLING
  - - AMPLIFICATION
  - - PROCESSING
- NETWORK OPERATING SYSTEMS

NETWORK ARCHITECTURE/TOPOLOGY

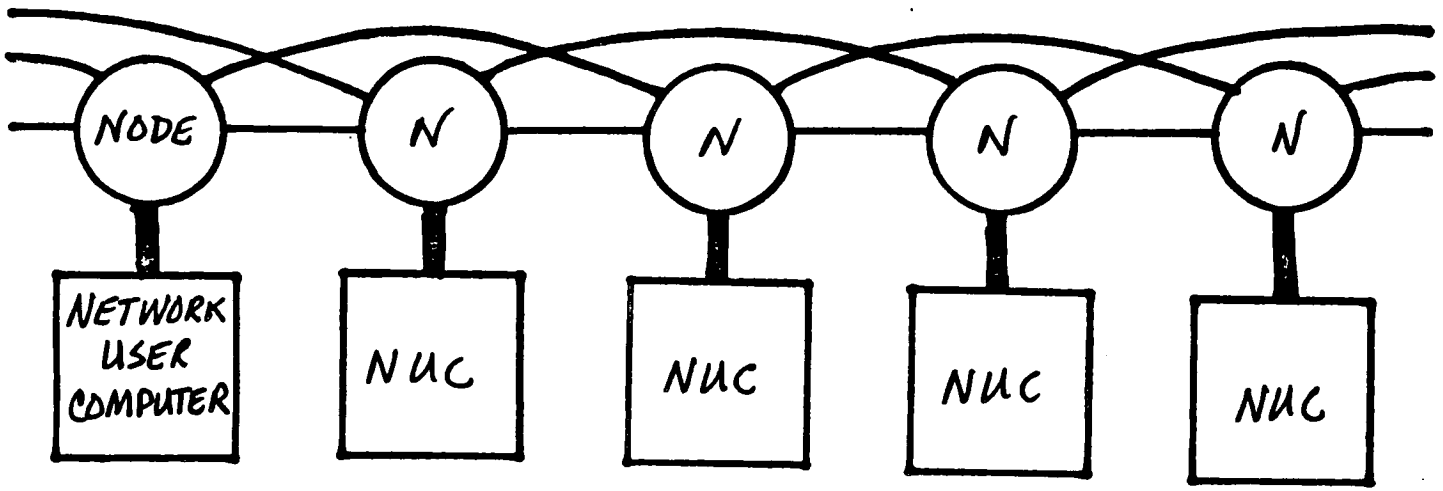


- o HIGH PERFORMANCE o
- o FAULT TOLERANT o





ELECTRONIC EMULATION OF OPTIC NETWORK

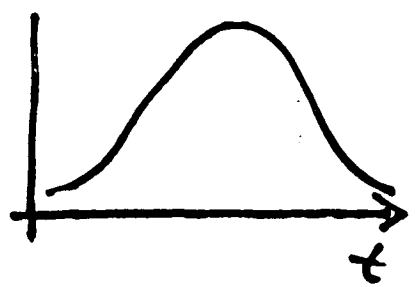


DATA ACCUMULTION
- EVENTS
- TIME

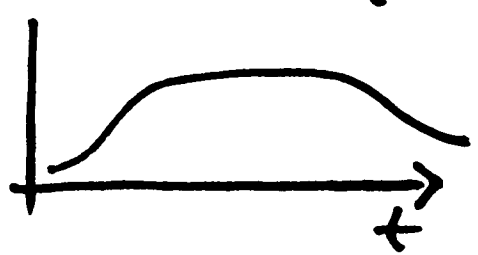
⇓

STATISTICAL EVALUATIONS

USER SERVICE DEMAND



USER SERVICE TIME

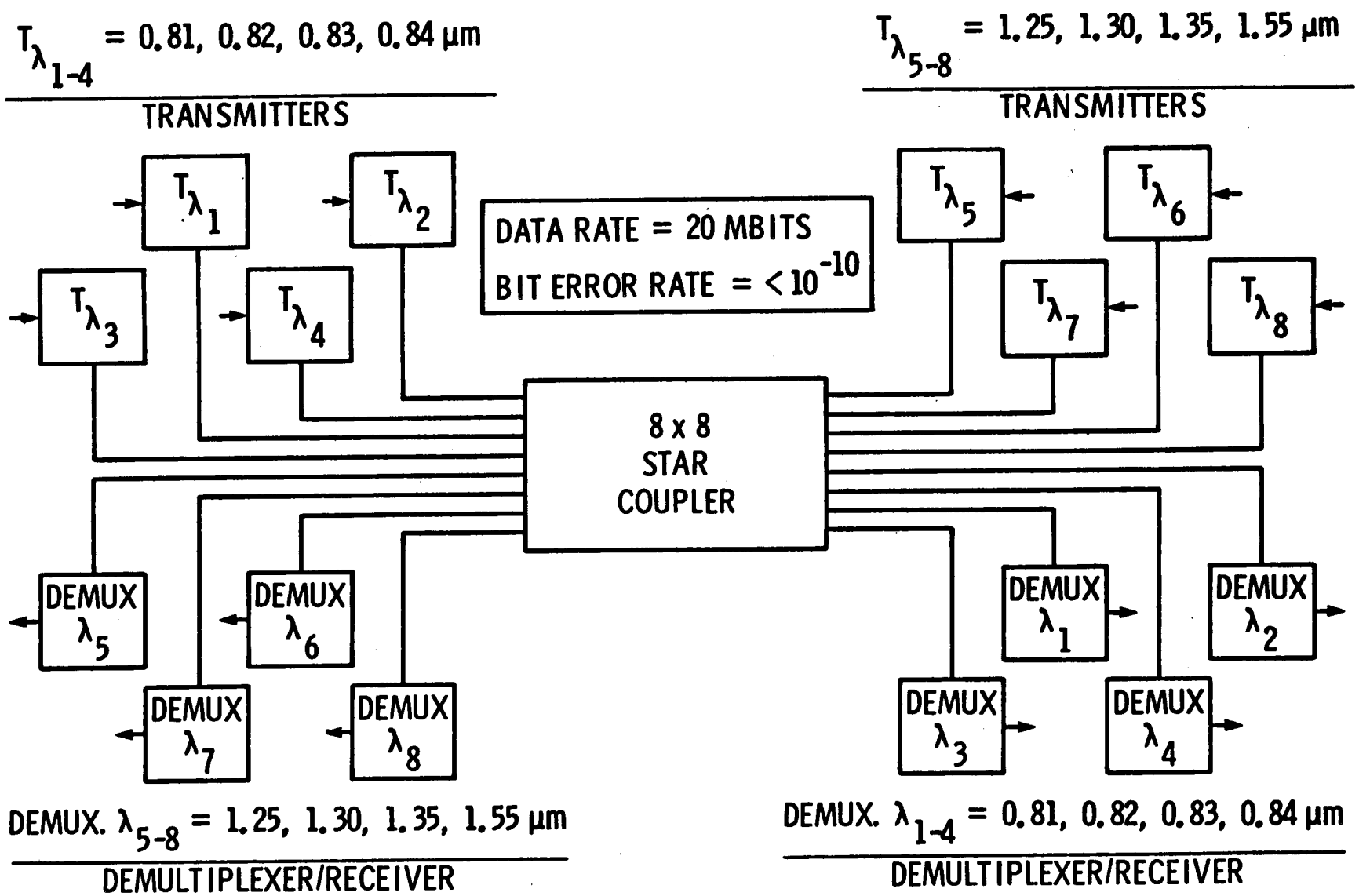


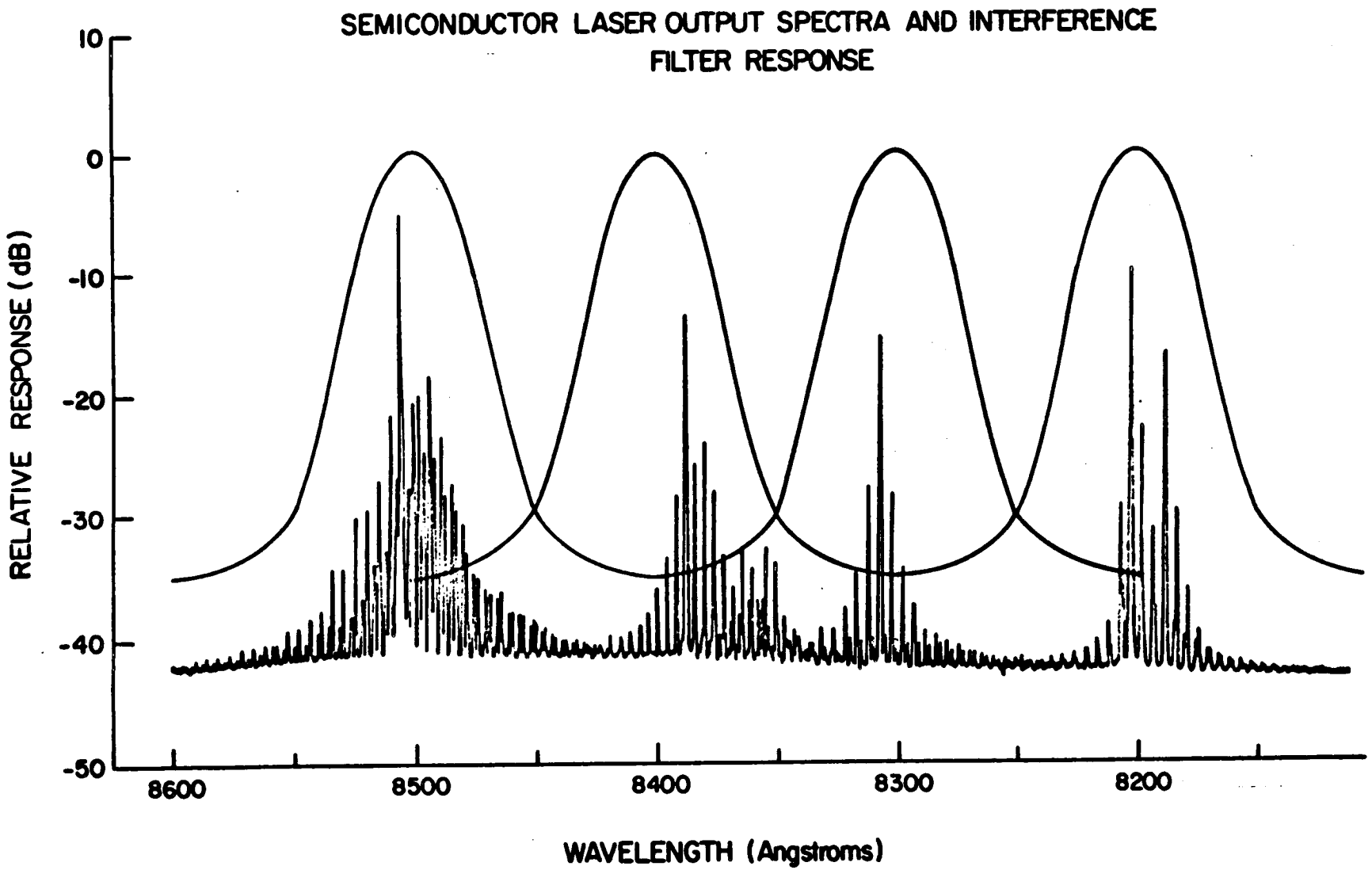
PARAMETRICALLY CONTROLED DISTRIBUTIONS

EVALUATION OF:
- FAILURE DETECT/RECOVER
- CENTRALIZED ROUTING
- DISTRIBUTED ROUTING
- FLOW CONTROL
- NETWORK UTILIZATION
- PEAK LOADING
- NUC/NODE INTERFACES

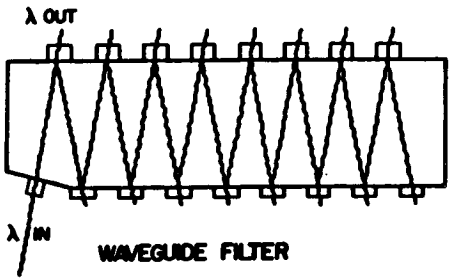
89-11

EIGHT CHANNEL WAVELENGTH DIVISION MULTIPLEXING STAR BUS

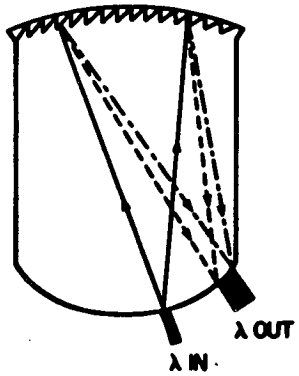



SEMICONDUCTOR LASER OUTPUT SPECTRA AND INTERFERENCE FILTER RESPONSE
RELATIVE RESPONSE (dB)
10
0
-10
-20
-30
-40
-50
8600
8500
8400
8300
8200
WAVELENGTH (Angstroms)

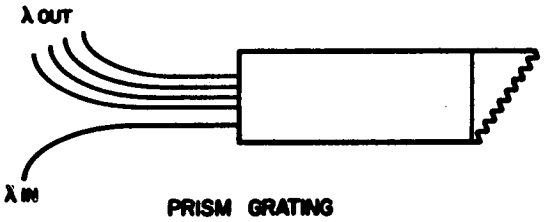
WAVELENGTH DIVISION MULTIPLEXING TECHNOLOGY



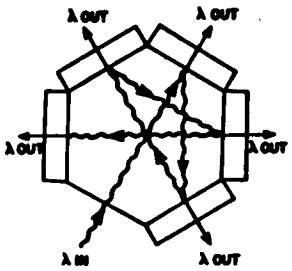
WAVEGUIDE FILTER



ROLAND GRATING

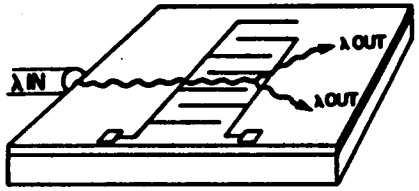


PRISM GRATING

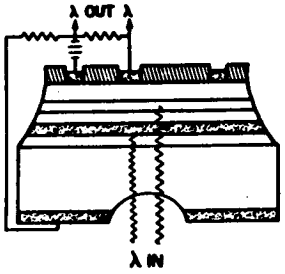


POLOGON WAVEGUIDE

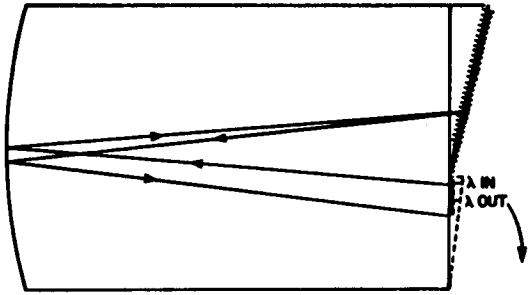
WDM DEMULTIPLEXERS



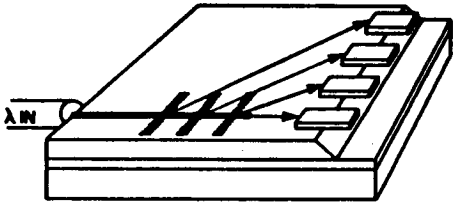
SURFACE ACOUSTIC WAVE



WAVELENGTH PHOTODETECTOR



LITTROW GRATING



INTEGRATED GRATING

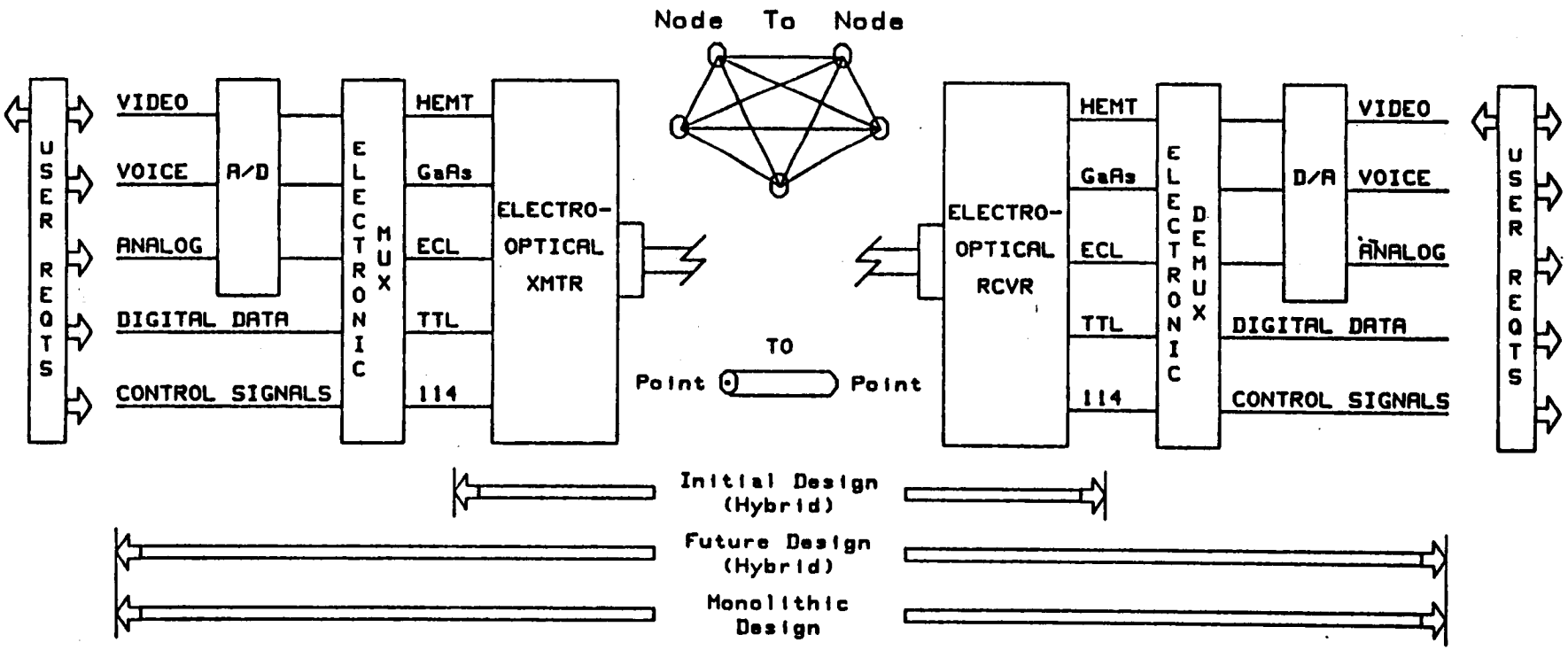
WDM LASER SOURCE WAVELENGTH STABILITY

VARIABLE	OBSERVABLE	CONTROL
TEMPERATURE	MODE STRUCTURE, 3 A/^{o} C MODE HOPPING	T.E. - 0.1^{o} C OP. @ I_{th}
DUTY FACTOR (10-90%)	WAVELENGTH SHIFT, 8 A	50% DF
OPTICAL FEEDBACK	LASER COUPLING END REFLECTION $\pm$22 A	WEDGE FIBER, A.R. COATING, FUSION SPLICING
LIFETIME 5,000 hrs @ 70° C 10,000 hrs @ 70° C	WAVELENGTH SHIFT -38 A -10 A	DEVICE FABRICATION, DEVICE DESIGN, MATERIAL CONTROL

Fiber Optic Common Transmitter/Receiver Modules

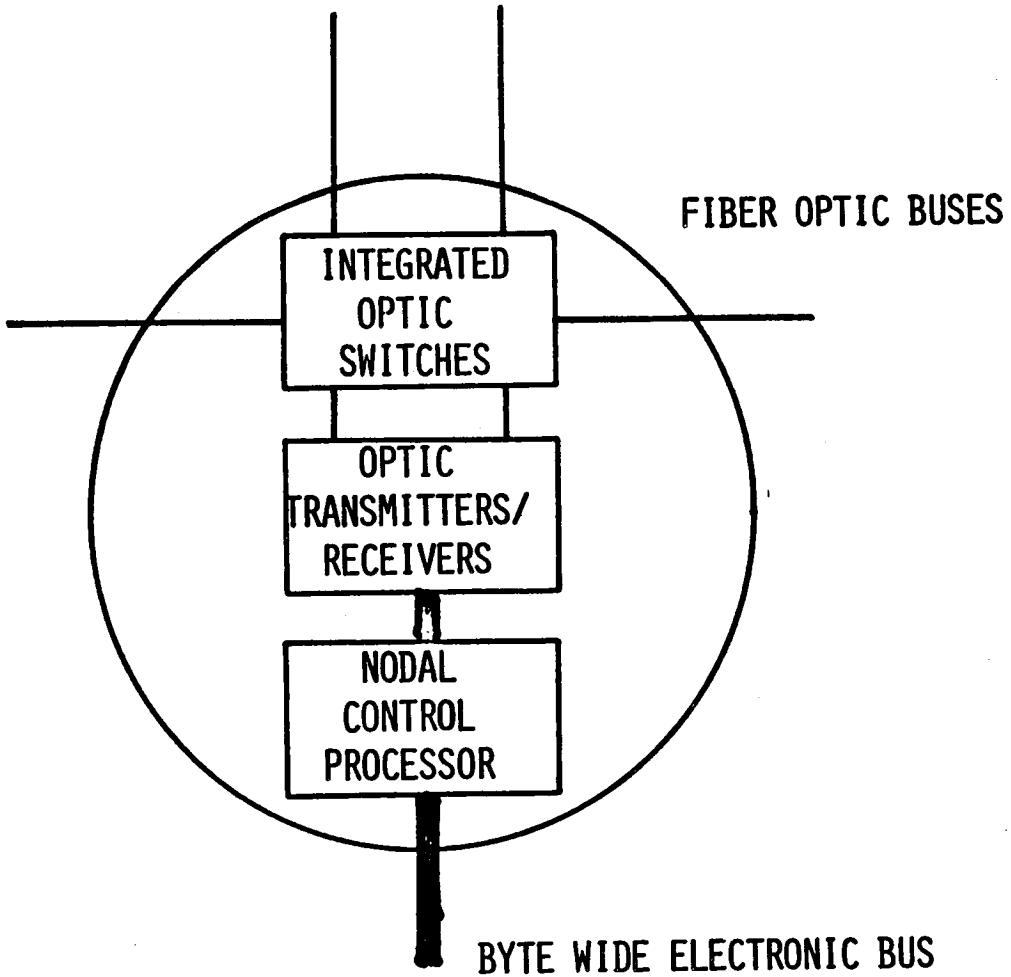
DOD/NASA

Network Connections



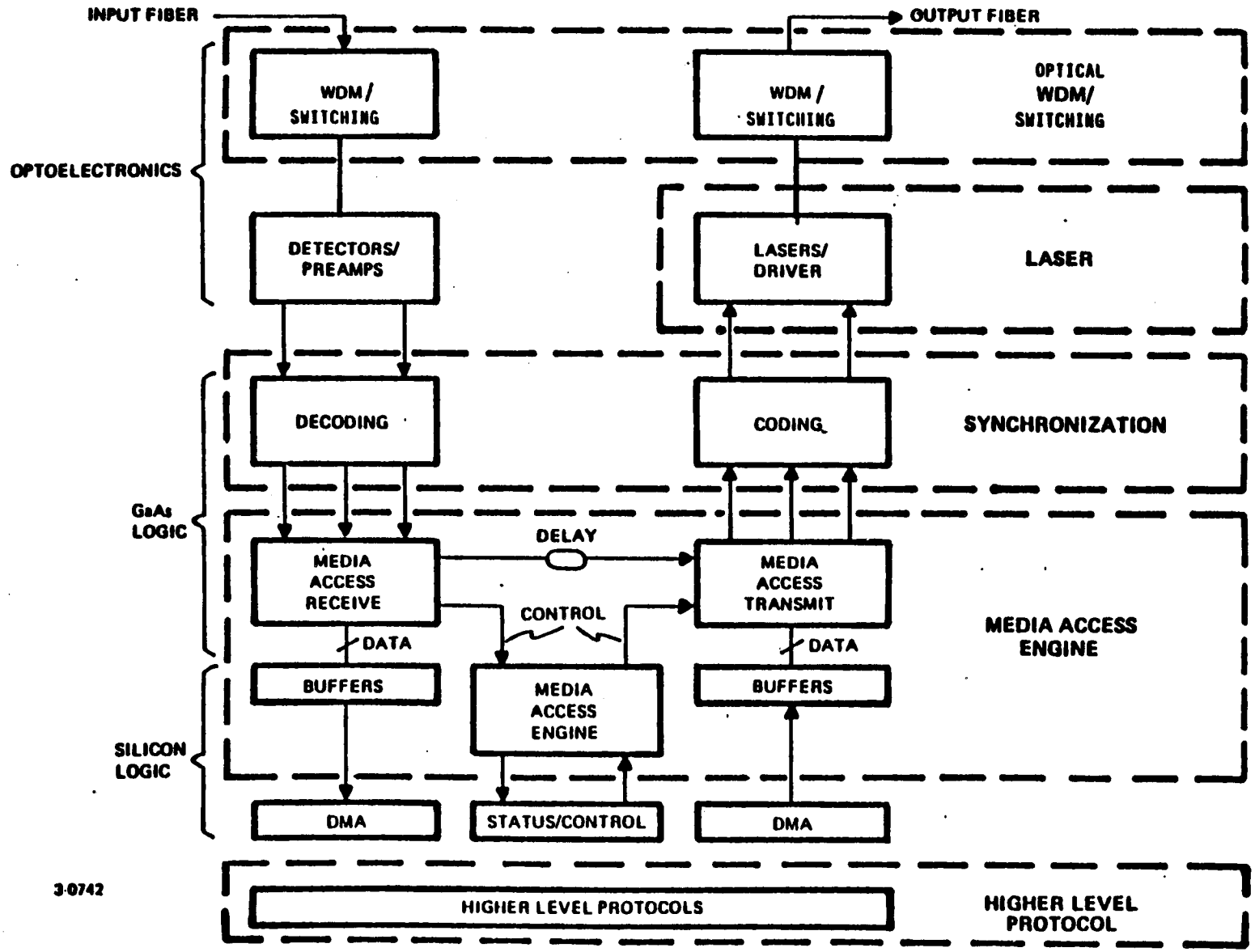
09/28/84

NASA - LANGLEY
H.D. HENDRICKS



ADAPTIVE NODE DEFINITION

TECHNOLOGY PARTITIONING OF NODE INTERFACE UNIT

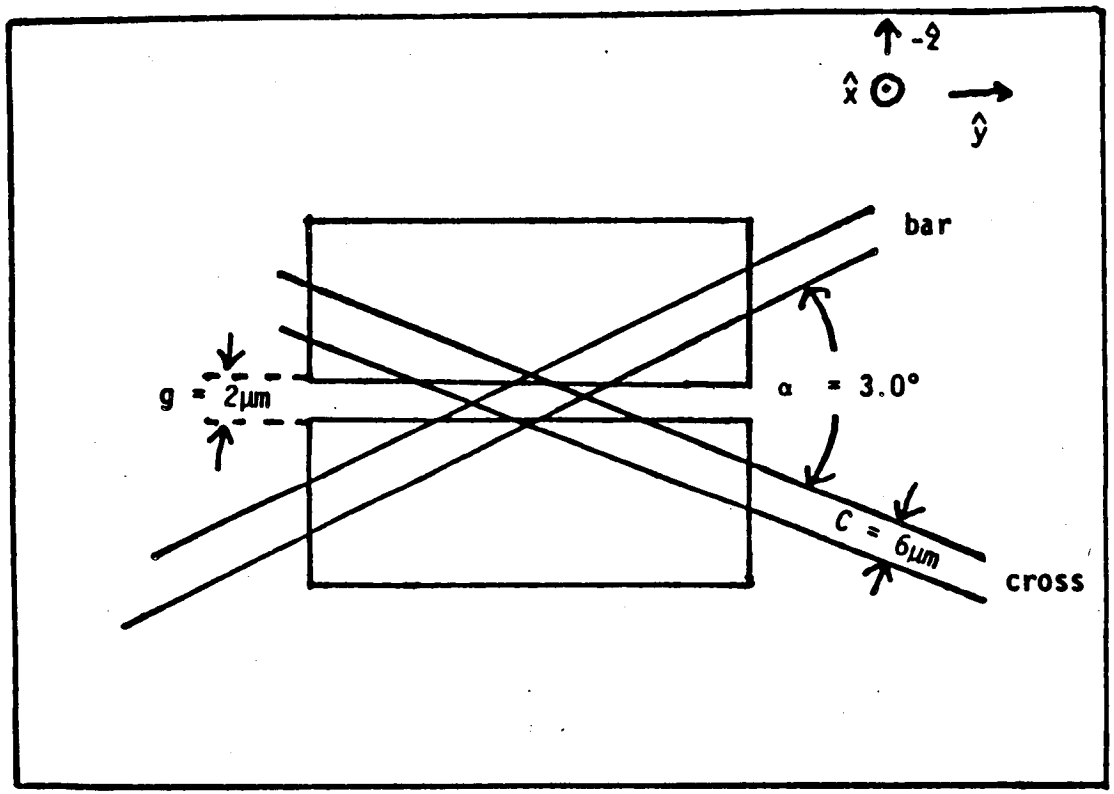


3-0742

INTELLIGENT OPTIC NODE TECHNOLOGY TIMELINE

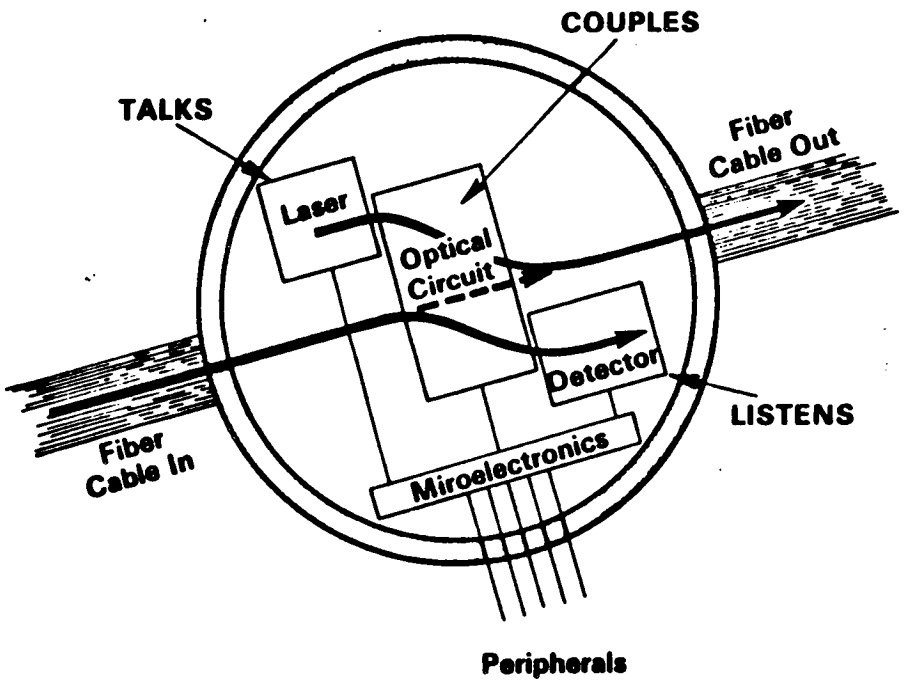
FUNCTIONS \ TIME	NEAR TERM (1-2 YEARS)	MEDIUM TERM (3-5 YEARS)	LONG TERM (5-10 YEARS)
• E/O	GaAlAs (discrete)	GaAlAs with drive/ detector electronics	Monolithic GaAs
• O/E	Si		
• Fiber	Single mode, non-polarization preserving		polarization preserving?
• Taps, Delay	Fiber	SAW	TBD
• Amplification	Si	GaAs	Monolithic GaAs
• Switching	$LiNbO_3$ (bulk)	$LiNbO_3$ / ZnO ?	ZnO? / ALGaAs
• Synchronization	Si / GaAs	GaAs (discrete)	Monolithic GaAs
• Frame/Address Recognition	Fiber / GaAs	SAW / GaAs	TBD
• Conflict Resolution	Si / GaAs	GaAs	Monolithic GaAs
• Routing	N/A	Si / GaAs (discrete)	
• Higher Level Protocols		Si	

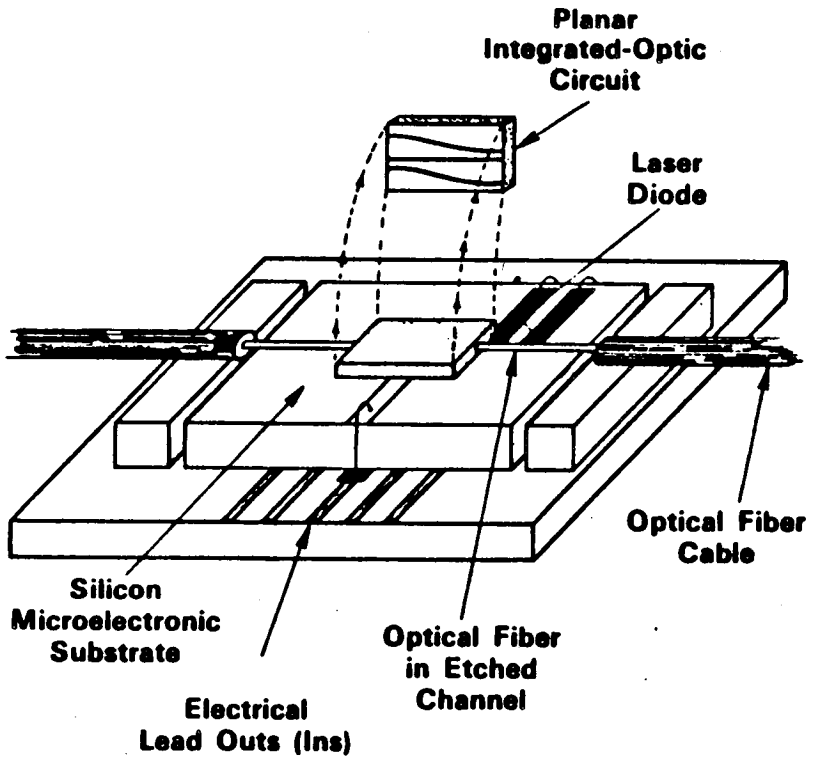
OPTICAL SWITCH DEVELOPMENT



Voltage	bar	cross
0 volts	40	60
+40 volts ($-\hat{z}$ is +)	90	10
-20 volts	10	90
-40 volts	40	60

ADAPTIVE OPTIC NODE CONCEPT





COMMON FEATURES FOR ALTERNATIVE DISTRIBUTED OPTICAL SWITCHING ARCHITECTURES

	FUNCTIONS \ ARCHITECTURE	LINEAR/STAR BUS	RING BUS	CIRCUIT SWITCH MESH	PACKET SWITCH MESH
PHYSICAL LAYER	TRANSMITTER/ RECEIVER	BURST ASYNC	SYNCHRONOUS	BURST ASYNC	
	SWITCH	NO			
	COUPLER				
	CHANNELIZATION (WDMUX-WDDMUX)				
	AMPLIFIER		COMMON FEATURES		
	DELAY				
DATA LINK	ADDRESS COMPARE				
	CONFLICT RESOLUTION			SLOW	FAST
	ROUTING/GATEWAY				
HIGH LEVEL PROTOCOL	HI LEVEL PROTOCOL	RING OR STAR COMMON.		MINIMAL	SIMILAR TO RING OR STAR

TABLE (1)

NETWORK OPERATING SYSTEM STATE-OF-ART

"ALMOST ALL WORK ON 'DISTRIBUTED' SYSTEMS IN GENERAL AND 'DISTRIBUTED'/NETWORK OPERATING SYSTEMS IN PARTICULAR HAS BEEN EVOLUTIONARY TO THE EXTREME . . . SIMPLE ADAPTATIONS OF CENTRALIZED ONES, BURDENED BY INAPPROPRIATE AND EVEN COUNTER PRODUCTIVE ARTIFACTS. THE INEFFECTIVENESS OF CONSTRUCTING AIRPLANES WHICH FLY BY FLAPPING THEIR WINGS WAS RECOGNIZED EARLY; BUT CORRESPONDING REALIZATION ABOUT DISTRIBUTED SYSTEMS HAVE LARGELY NOT YET TAKEN PLACE . . ."
JENSEN (CMU) - ARCHONS - 1984

- NO UPGRADE OF GROUND OR EMBEDDED O/S WILL SUPPORT REQUIREMENTS.
- "WITHOUT ADVANCES IN O/S METHODOLOGIES . . . LIKELY NOT TO SEE SUBSTANTIAL IMPROVEMENTS IN RELIABILITY, INCREASE POWER AND FLEXIBILITY" (MCKENDRY - GA TECH. - CLOUDS)

EMBEDDED NETWORK STRUCTURE

Feedback Control -- Timeliness of information
Data Management -- No backlog of information

* STRUCTURE

  Multiple paths for reliability
  Parallel paths for time-critical and regular data

* ADVANTAGES

  Super reliability & flexibility
  Excellent performance under widely varying loads

* PROBLEMS

  Network information, routing & control
  Algorithms for reconfiguration
  Priority access firmware

NETWORK OPERATING SYSTEM RESEARCH

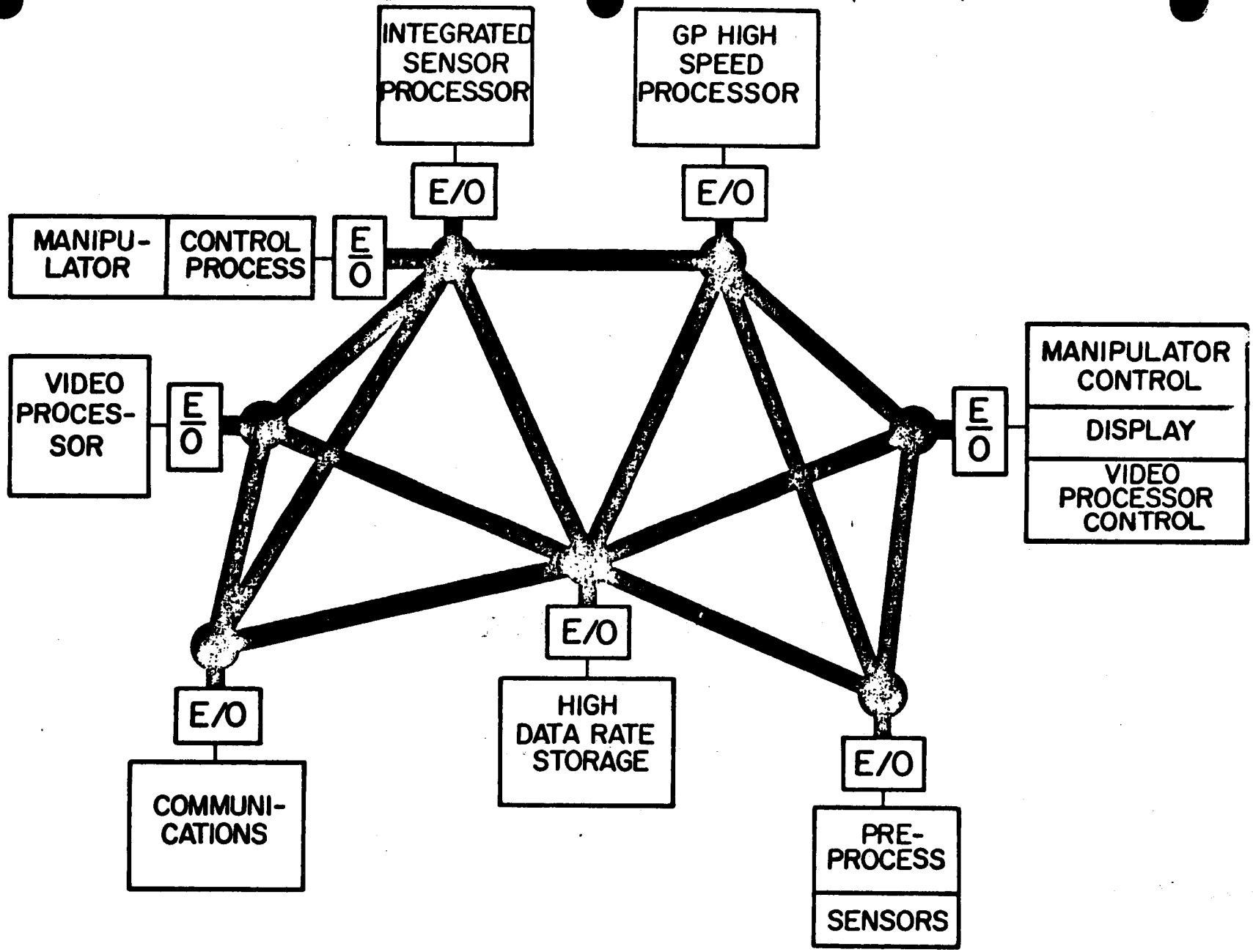
KEY TO NETWORK O/S . . . IDENTIFY, INTEGRATE, IMPLEMENT ARCHITECTURE FEATURES TO SUPPORT O/S MODEL (HARDWARE - FIRMWARE - O/S LANG. - O/S KERNEL)

NETWORK O/S ARCHITECTURE MODELS (CONCURRENCY - RELIABILITY)

- DISTRIBUTED DATA BASE
- S - CONVERSATIONS
- CLIENT - SERVER
- TRANSACTIONS (OBJECT & ACTION)
- DYNAMIC GROUP COMMUNICATION

DISTRIBUTED DEBUGGING

MULTIPATH TOPOLOGY FOR TIME CRITICAL NETWORKING



[EXAMPLE HIGH PERFORMANCE NETWORK]

Honeywell

VIDEO IMAGE PROCESSING

FOR

SPACE STATION OPERATIONS

KENNETH HOYME
SUDHAKAR YALAMANCHILI
RICHARD FUNDAKOWSKI

HONEYWELL SYSTEMS AND RESEARCH CENTER
MINNEAPOLIS, MINNESOTA

48-11

85V35

OVERVIEW

This talk centers on video image processing functions and architectures which are relevant to space station activities. First a number of activities are identified. Next a set of image processing functions are discussed and a few examples given. Image processing architectures are then addressed and an example given. Finally we discuss future trends in image processing and what needs must be addressed for any space station implementation.

OVERVIEW

Honeywell

- SPACE STATION APPLICATIONS
- CATEGORIZE IMAGE PROCESSING FUNCTIONS
- EXAMINE SOME SPECIFIC EXAMPLES
- CATEGORIZE IMAGE PROCESSING ARCHITECTURES
- EXAMINE SOME SPECIFIC EXAMPLES
- DISCUSS FUTURE TRENDS/NASA'S NEEDS

85V35

EXAMPLE SPACE STATION APPLICATIONS OF VIDEO IMAGE PROCESSING

A number of application areas have been identified which use video information. A few examples are given here along with the type of processing which is required. During rendezvous the incoming object may be identified and displayed to the crewmember using highlighting. Due to the distances involved, the object will be a point target. During proximity operations the target may be tracked and orientation, position and velocity determined. Other applications include the use of machine vision for automated or assisted inspection.

SPACE STATION APPLICATIONS OF VIDEO IMAGE PROCESSING

Honeywell

RENDEZVOUS

- TARGET IDENTIFICATION
- TARGET TRACKING FOR CROSS RANGE VELOCITY AND POSITION ESTIMATION
- POINT TARGET DETECTION

PROXIMITY OPERATIONS

- TARGET TRACKING FOR TARGET ORIENTATION, POSITION AND VELOCITY ESTIMATION

DATA MANAGEMENT

- BANDWIDTH COMPRESSION FOR DATA MOVEMENT AND ARCHIVING

INSPECTION

- MACHINE VISION TECHNIQUES FOR VERIFICATION OF SPACE STATION STRUCTURAL INTEGRITY AND DETECTION AND CLASSIFICATION OF DEFECTS

COMMUNICATION AND TRACKING

- BANDWIDTH COMPRESSION FOR DOWNLINK TRANSMISSION
- MULTI-TARGET TRACKING FOR AREA TRAFFIC CONTROL
- TARGET DETECTION AND IDENTIFICATION FOR AREA TRAFFIC CONTROL

CONSTRUCTION

- VERIFICATION OF CONSTRUCTION STEPS

85V35

11-88

REAL-TIME IMAGE PROCESSING CATEGORIZATION

This is a comparison of image processing categories against a set of attributes. There are three image processing categories. The first is the Image Pixel category consisting of point, window and image operations. Second is the Image Region category consisting of segmentation, feature extraction and encoding operations. Finally, structural, feature and distance operations are representative of the symbolic category.

A set of representative operators are shown for each operation type. The data type and typical data structures are also given. The last column identifies the typical architecture class or control scheme used to execute the operation.

REAL-TIME IMAGE PROCESSING CATEGORIZATION

Honeywell

ATTRIBUTES

	OPERATORS	DATA	DATA STRUCTURES	ARCHITECTURES
IMAGE PIXEL				
POINT	DETECTOR COMPENSATION HISTOGRAMMING CHANGE DETECTION IMAGE CORRELATION	PIXELS	IMAGE ARRAYS: GREYSCALE	SIMD
WINDOWS	EDGE ENHANCEMENT LINEAR FILTERING NONLINEAR FILTERING	PIXELS	SUBIMAGE ARRAYS: GREYSCALE	SIMD
IMAGE	DISCRETE FOURIER TRANSFORM HADAMARD TRANSFORM	PIXELS	IMAGE ARRAYS: GREYSCALE	SIMD
IMAGE REGION				
SEGMENTATION	REGION GROWING SUPERSLICE CONNECTIVITY RELAXATION BOUNDARY TRACING	PIXELS	SUBIMAGE ARRAYS: GREYSCALE, BINARY EDGE, INTENSITY	MIMD
FEATURE EXTRACTION	MOMENTS CENTROID OBJECT EXTENTS	FEATURES, REAL VALUED	REAL VALUED ARRAYS AND LINKED LISTS	PIPELINE
ENCODING	CHAIN CODING FOURIER DESCRIPTORS	SILHOUETTES	LINKED LIST OF REAL AND INTEGER VALUES	MIMD
SYMBOLIC				
STRUCTURAL	TEMPLATE MATCHING GRAPH CORRELATION	SILHOUETTES CORRELATION VALUES	INTEGER, LINKED LISTS, GRAPHS CORRELATION ARRAYS	PIPELINE
FEATURE	COVARIANCE LINEAR DISCRIMINANT FEATURE MATCHING	REAL VALUES	M-DIMENSIONAL REAL ARRAYS	PIPELINE
DISTANCE	EUCLIDEAN DISTANCE DECISION SMOOTHING OBJECT CLASSIFICATION	REAL, INTEGER AND BOOLEAN	DECISION SEQUENCES DECISION CONFIDENCE ARRAYS	MIMD

85V35

REAL-TIME IMAGE PROCESSING CATEGORIZATION (CONT.)

This table shows the typical operators used in each operational class to perform a set of example image processing functions. The applications shown here are Point Target Detection, Target Tracking, Target Identification and Bandwidth Compression.

REAL-TIME IMAGE PROCESSING CATEGORIZATION (CONT'D)

Honeywell

FUNCTIONS

	POINT TARGET DETECTION	TARGET TRACKING	TARGET IDENTIFICATION	BANDWIDTH COMPRESSION
IMAGE PIXEL POINT	• DETECTOR COMPENSATION • CHANGE DETECTION	• CONTRAST ENHANCEMENT	• HISTOGRAM MODIFICATION	
WINDOWS	• EDGE/BRIGHT COINCIDENCE	• EDGE ENHANCEMENT • BACKGROUND ESTIMATION	• EDGE ENHANCEMENT • BACKGROUND ESTIMATION	• EDGE OPERATORS • TEXTURE CALCULATION
IMAGE	• SCENE TRANSFORM	• THRESHOLDING – EDGE – INTENSITY	• BACKGROUND SUPPRESSION	• HADAMARD ENCODE
IMAGE REGION SEGMENTATION	• EDGE THRESHOLD • BRIGHT THRESHOLD	• REGION GROWING • CONNECTIVITY	• REGION GROWING • CONNECTIVITY	• LINE/CURVE EXTRACTION
FEATURE EXTRACTION	• SIZE/SHAPE EXTRACTION	• COARSE SIZE CALCULATION	• SIZE/SHAPE CALCULATION	• REGION ATTRIBUTE CALCULATION
ENCODING		• TARGET OUTLINE ENCODING	• TARGET OUTLINE ENCODING	• EDGE ENCODING
SYMBOLIC STRUCTURAL	• POSITIONAL ASSOCIATION (PERSISTENT, CONSISTENT)	• FRAME TO FRAME *SILHOUETTE ASSOCIATION	• SILHOUETTE MATCHING	• SCENE TRANSFORM UPDATE
FEATURE	• SIZE/SHAPE DISCRIMINATION	• FEATURE CORRELATION (FRAME-TO-FRAME)	• FEATURE CORRELATION (VS PROTOTYPES)	
DISTANCE	• VOTE/CONFIDENCE ACCRUAL • DECISION SMOOTHING		• TARGET IDENTIFICATION DECISION	

85V35

ARCHITECTURES FOR IMAGE PROCESSING

This table is a comparison of three different aspects of parallel architectures against a number of attributes. Processors are the basic functional units which perform operations on the data. Interconnection indicates the method with which processors or groups of processors are connected. Mode indicates how the processors are controlled.

The attributes are

- o Performance - A relative measure of attainable throughput.
- o Level - Indicates the image processing category which is suited for the particular architecture.
- o Programmability - The ease with which software can be developed for a processor.
- o Control - The ease with which control schemes can be developed or coded for the architecture.
- o Flexibility - A measure of how many different operations or class of operations can be executed on the processor.
- o Fault Tolerance - A measure of how inherently tolerant the architecture is to faults. All architectures can be made fault tolerant with varying degrees of difficulty.

ARCHITECTURES FOR IMAGE PROCESSING

Honeywell

ATTRIBUTES

	PERFORMANCE	LEVEL	PROGRAMMABILITY	CONTROL	FLEXIBILITY	FAULT TOLERANCE	EXAMPLES
PROCESSORS							
FUNCTIONALLY DEDICATED	VERY HIGH	IMAGE PIXEL	NONE	N/A	POOR	POOR	SYSTOLIC ARRAYS
SPECIAL PURPOSE MICROPROGRAMMABLE	HIGH	IMAGE PIXEL/REGION	DIFFICULT	N/A	FAIR	DEPENDS	HONEYWELL EOSP ILLIAC – IV
GENERAL PURPOSE PROGRAMMABLE	LOWER	SYMBOLIC	SIMPLER	N/A	GOOD	DEPENDS	WESTINGHOUSE GPC TI – DPU HONEYWELL ADOP-V
INTERCONNECTION							
FIXED	HIGH	ALL	N/A	SIMPLE	POOR	FAIR	NON-VON, MPP
BUS	CAN BE A BOTTLENECK	ALL	N/A	MODERATE	FAIR	CAN BE GOOD	ZMOB PICAP II
RECONFIGURABLE	CAN BE HIGH	SYMBOLIC	N/A	COMPLEX	GOOD	GOOD	PASAM, CHIP PUMPS
CONTROL MODE							
SIMD	HIGH	IMAGE PIXEL	N/A	SIMPLE	FAIR	DEPENDS	HONEYWELL EOSP MPP
PIPELINED	HIGH	IMAGE PIXEL/ IMAGE REGION	N/A	CAN BE COMPLEX	FAIR	DEPENDS	CRAY, MMBC
MIMD	CAN BE HIGH	IMAGE REGION/ SYMBOLIC	N/A	CAN BE COMPLEX	GOOD	GOOD	PUMPS, CHIP

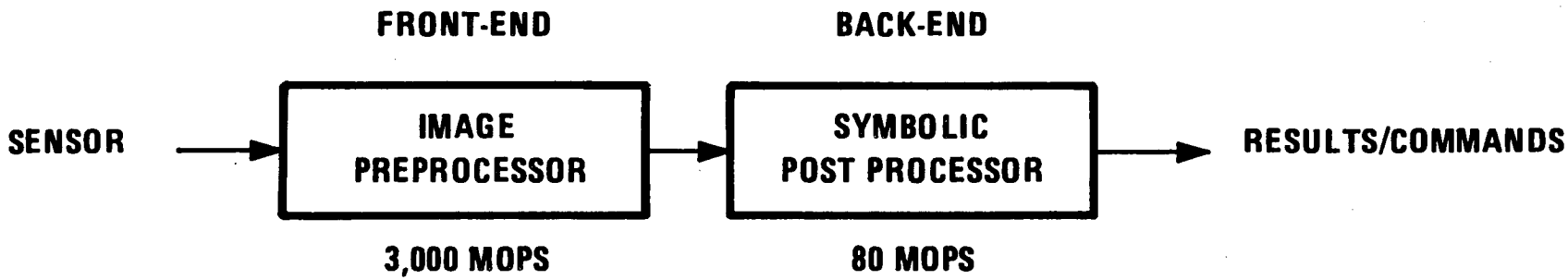
85V35

TOP-LEVEL IMAGE PROCESSING ARCHITECTURE

This is a top-level view of an image processor being developed for the Imaging Sensor Autoprocessor program. It consists of a very high throughput front-end processor tailored to perform low-level image processing functions. The results are passed to a symbolic post-processor which is suited for the high-level, decision making operations.

TOP-LEVEL IMAGE PROCESSING ARCHITECTURE

Honeywell



- 2-STAGE ARCHITECTURE
- FIRST STAGE TAILORED TO IMAGE-PIXEL, IMAGE REGION OPERATIONS
- SECOND STAGE TAILORED TO SYMBOLIC OPERATIONS

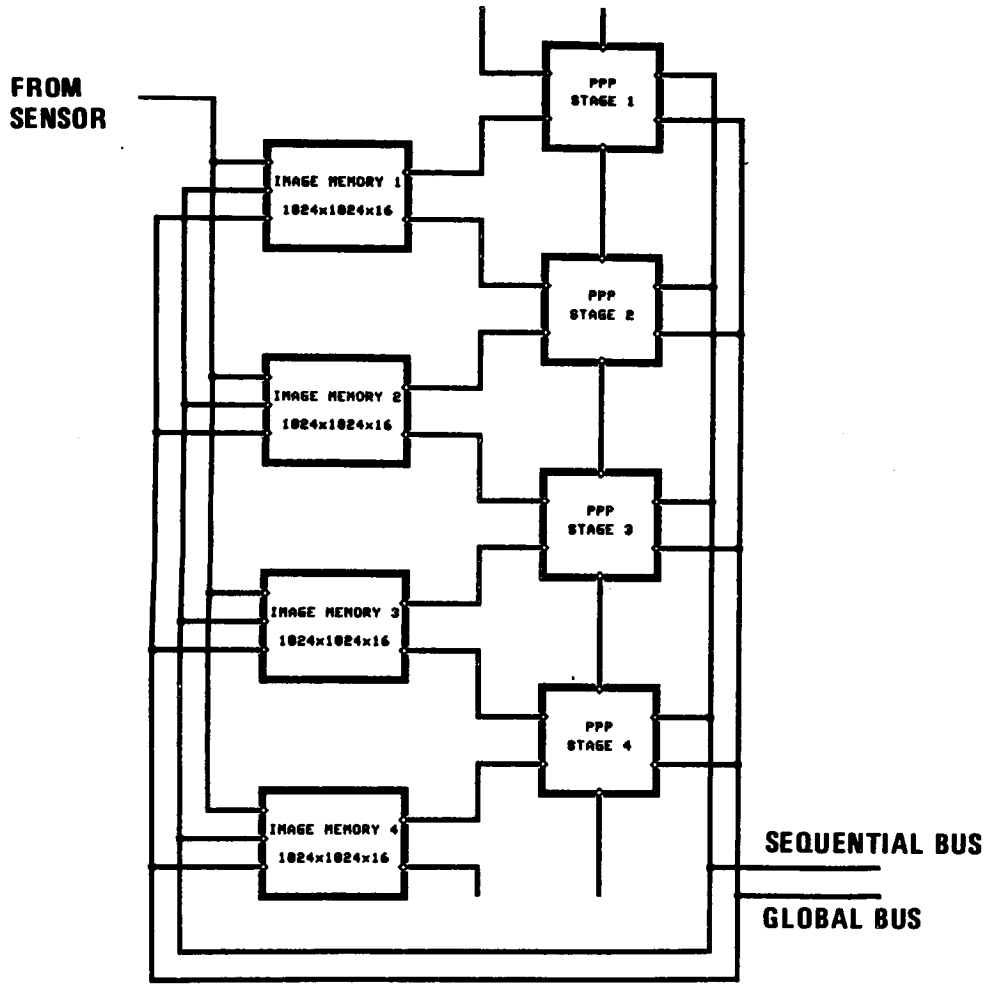
85V35

IMAGE PREPROCESSOR ARCHITECTURE

The image preprocessor consists of a set of SIMD stages interconnected by a set of image memories. Data can be removed from or placed in any image memory. Block data can be moved to the back-end over the sequential bus. Task coordination is performed over the global bus.

IMAGE PREPROCESSOR ARCHITECTURE

Honeywell



- IMPLEMENTS HIGH THROUGHPUT, MEMORY INTENSIVE IMAGE PROCESSING FUNCTIONS
  - MOVING TARGET DETECTION
  - INTEREST REGION LOCATION
- MULTIPLE – SIMD CONFIGURATION

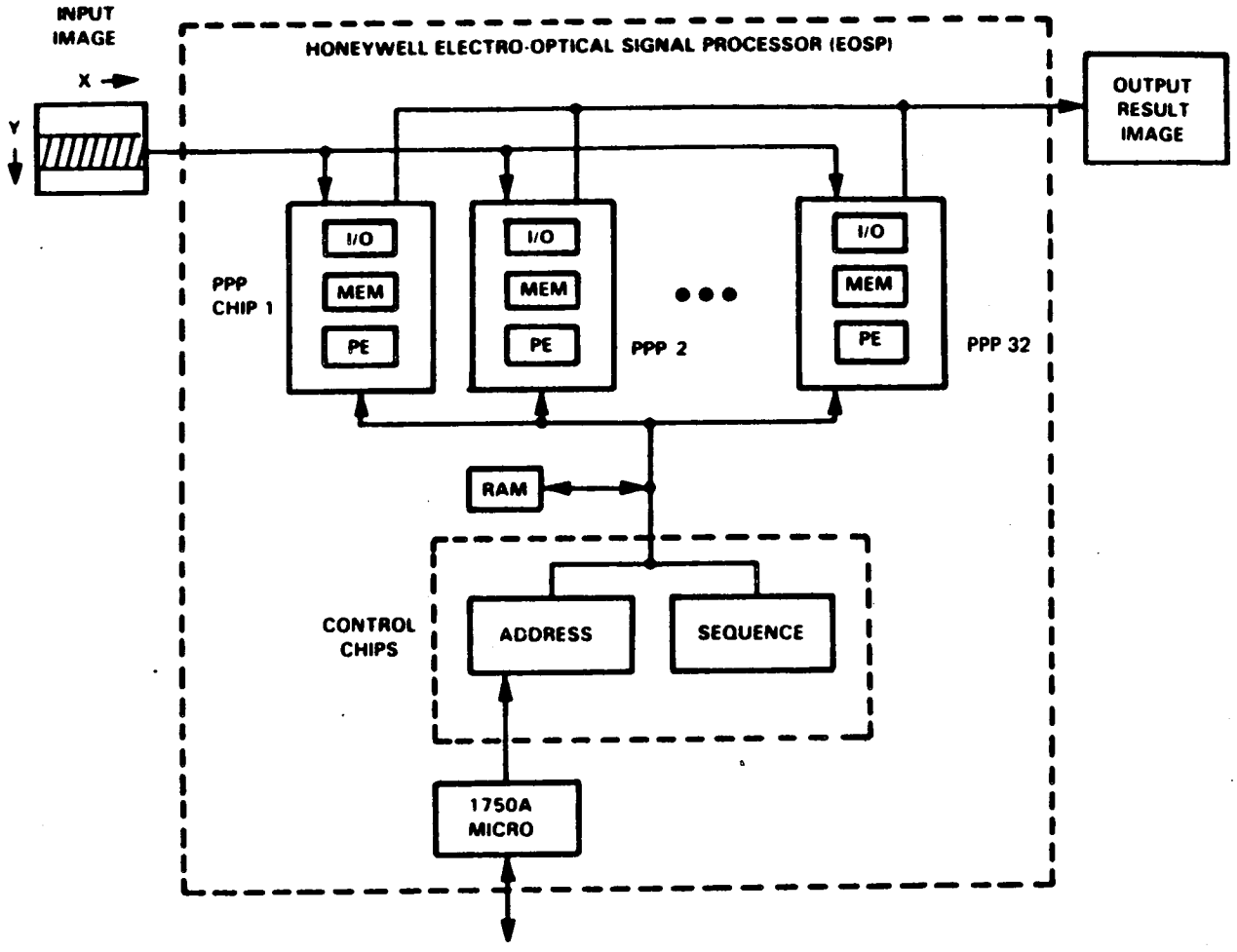
85V35

PPP STAGE

The Parallel Programmable Pipeline (PPP) stages used in the image preprocessor are SIMD microprogrammable processors made from the Honeywell VHSIC EOSP chip set. It consists of a set of 32 processing elements, each with local memory, interconnected by a ring bus. They are controlled in a SIMD mode by a pair of control chips. The 1750A microprocessor (An F9450) performs coordination, synchronization and scheduling tasks between the various PPP stages.

PPP STAGE

Honeywell



- SIMD, MICROPROGRAMMABLE
- 800 MIPS FOR 32 PARALLEL PROGRAMMABLE PIPELINE CHIPS

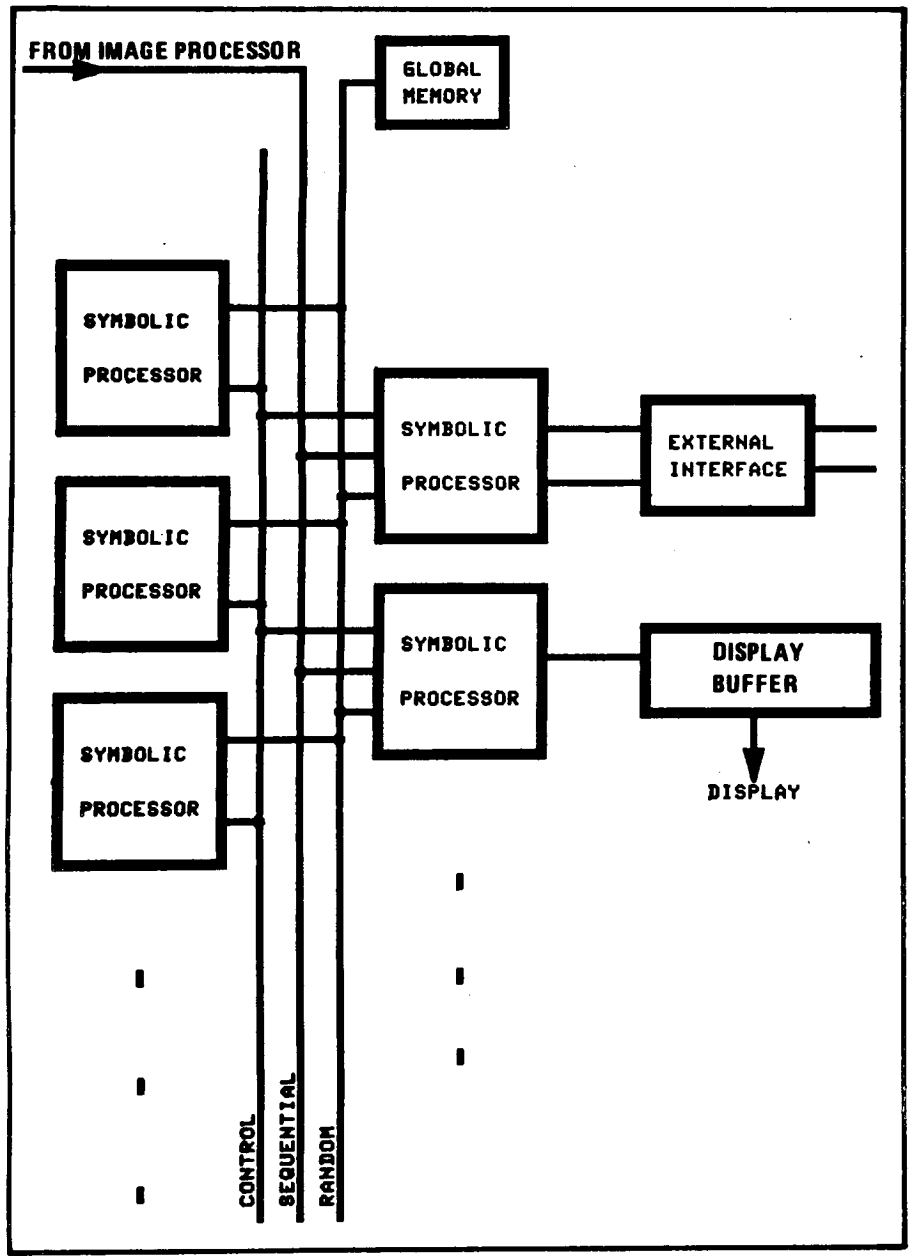
84V140

SYMBOLIC POST-PROCESSOR ARCHITECTURE

The post-processor consists of a set of symbolic processors executing in a MIMD mode. Task coordination is provided over the global bus. Data is brought in from the front-end over the sequential bus.

SYMBOLIC POST-PROCESSOR ARCHITECTURE

Honeywell



- MIMD ARCHITECTURE
- TASK LIST IN GLOBAL MEMORY
- 80 MIPS TOTAL THROUGHPUT

83V151

FUTURE TRENDS IN IMAGE PROCESSING

A number of trends will impact the development of an image processor for the space station. Algorithms are still being developed particularly in the area of image understanding where AI techniques are being applied. Other advances are occurring in computer architecture with the development of hardware for support of AI languages, tools for rapid development of VLSI hardware, and faster interconnection schemes. Wafer scale integration may prove to be the ideal technology for large parallel computing structures.

Programming tools are being developed to aid in the development of software for parallel systems. This includes automatic program restructuring as well as microcode compilers. Another technology being studied is integrated optical interconnects where chip-to-chip signals are done on optical fibers. Finally, research is continuing into alternative processing technologies such as optical processors.

FUTURE TRENDS IN IMAGE PROCESSING

Honeywell

- ALGORITHM ADVANCES IN THE AREA OF AUTONOMOUS IMAGE UNDERSTANDING
- ARCHITECTURAL ADVANCES IN
  - AI MACHINES
  - RAPID DESIGN OF DEDICATED HARDWARE
  - FAST INTERCONNECTION SCHEMES
- WAFER SCALE INTEGRATION
- PROGRAMMING TOOLS FOR PARALLEL SYSTEMS AND MICROCODING
- INTEGRATED OPTICAL INTERCONNECTS
- ALTERNATIVE PROCESSORS

NASA's NEEDS

In addition to the growth in image processing technology, NASA needs to address other issues. Among these are the development of space qualified hardware technologies. Of critical importance are size, weight, power, and radiation hardness issues. Also, since much of past image processing development has been driven by DoD ground-based needs, the algorithms must be evaluated and tuned for the space image environment.

An example of a NASA program addressing these issues is the Video Image Processor program funded by NASA Langley Research Center to Honeywell Systems and Research Center.

NASA's NEEDS

Honeywell

- DEVELOPMENT OF SPACE QUALIFIED HARDWARE
  - SIZE, WEIGHT, POWER RESTRICTIONS
  - RADIATION HARDNESS
- EXAMINATION OF IMAGE PROCESSING ALGORITHMS FOR PERFORMANCE IN SPACE ENVIRONMENT
- EXAMPLE OF THIS KIND OF PROGRAM – VIDEO IMAGE PROCESSOR: NASA LaRC
  - EXAMINING APPLICABLE ALGORITHMS, ARCHITECTURES, TECHNOLOGIES
  - WILL MAKE RECOMMENDATIONS CONCERNING SYSTEM ARCHITECTURE, DMS INTERFACE, ALGORITHMS

SIGNAL PROCESSING ELEMENTS AND COMPUTERS FOR PROXIMITY OPERATIONS

H. F. BENZ, LaRC
FEBRUARY 21, 1985

SPACE STATION

EMBEDDABLE PROCESSOR REQUIREMENTS

801-11

EMBEDDABLE PROCESSOR SYSTEM ASSUMPTIONS

CONSIDERING ALL PROCESSORS EMBEDDED IN ALL MODULES AND THE DATA MANAGEMENT SYSTEM AS A WHOLE

- MULTIPLE ARCHITECTURES
- MULTIPLE TYPES OF EACH ARCHITECTURE
- HIERARCHIAL CONTROL OF DISTRIBUTED PROCESSORS
- MODULAR - REPLACEABLE/REPAIRABLE/UPGRADABLE
- EVOLUTIONARY
- COMMON LANGUAGE INTERNAL INTERFACE
- SEPARABLE BY FUNCTIONAL REQUIREMENTS AND NECESSARY FAULT TOLERANCE
- ABILITY OF ARCHITECTURE AND OPERATING SYSTEM TO TRADE SYSTEM PERFORMANCE FOR FAULT TOLERANCE
- ALL SELF TESTABLE UNDER EXTERNAL CONTROL, BUILT-IN TEST TO CHIP LEVEL

I. COMMAND AND CONTROL LIFE DAMAGING/THREATENING (CORE)

FUNCTIONS

- SUPERVISION
- COMMUNICATION CONTROL
- CRITICAL PARAMETER CALCULATIONS/CONTROL
- EMERGENCY ACTIONS - RECONFIGURATION OF LOWER PRIORITY SYSTEMS
  - RESPONSE TO OUT OF NOMINAL BEHAVIOR

PERFORMANCE BOGEYS

- MATURE HW/SW - HIGHLY FIXED, VERIFIED PROGRAMS
- FULLY REDUNDANT/SELF-CORRECTING/NON-DEGRADABLE/FULLY SELF TESTABLE
- 5 MOPS
- BIT/BYTE
- 10 MBYTES HARD STORAGE

PROCESSOR SYSTEM BOGEYS/CAPABILITIES FOR C&C AT LEVEL 4*

PERFORMANCE ESTIMATES	83	86	92
MOPS INTEGER (16 BIT)			
MOPS FLOATING (32 BIT)	2-3	5	20
STORAGE	1 MBYTE	10 MBYTE	20 MBYTES
TRANSFER RATES EXTERNAL MBITS/SEC	100	300	1000
TECHNOLOGY			
A. TYPE	NMOS	CMOS	
B. DENSITY (LSI, VLSI, VHSIC)	LSI	VLSI	VHSIC I

* ESTIMATES BASED ON NASA SPACE SYSTEMS TECHNOLOGY MODEL V2.C13. EXTRAPOLATED WITH BEST WAG.

II. HEALTH AND STATUS DAY-TO-DAY SYSTEM MANAGEMENT (CORE/OPERATIONS)

FUNCTIONS

- GUIDANCE, NAVIGATION
- STRUCTURAL DYNAMICS
- LIFE SUPPORT/LIGHT/HEAT/ATMOSPHERE
- EXTERNAL ENVIRONMENT CONTROL
- SELF CHECK/NOTIFY C&C OF STATUS

PERFORMANCE BOGEYS

- HW/SW ADAPTABLE/REPROGRAMMABLE
- FAIL SAFE/FAULT TOLERANT BY RECONFIGURATION WITH DEGRADED PERFORMANCE/SELF TESTABLE
- BIT/BYTE - & FLOATING POINT CAPABILITY
- POWER INTERRUPTABLE ON COMMAND FOR 100 MS
- 10 - 100 MBYTE MIXED STORAGE
- 10 - 100 MBIT/S THROUGHPUT

PROCESSOR SYSTEM BOGEYS/CAPABILITIES FOR HEALTH/STATUS AT LEVEL 4*

PERFORMANCE ESTIMATES	83	86	92
MOPS	5	10	100
STORAGE MBYTES	5	10	100
TRANSFER RATES			
EXTERNAL MBITS/SEC	~ .100	500	2000
TECHNOLOGY			
BASELINE			
A) TYPE	NMOS	NMOS/CMOS	CMOS/GaAs
B) DENSITY	VLSI	VHSIC I	VHSIC 2

III. DATA HANDLING PROVIDED SERVICES TO USERS (SCIENCE)

FUNCTIONS

- SYSTEM FULL DIAGNOSTICS/ARCHIVE
- EXPERIMENTAL DATA PROCESSING/ARCHIVE
- INSTRUMENT MANAGEMENT
- COMMUNICATIONS INTERFACE FOR DATA
- NOT HI RELIABLE

PERFORMANCE BOGEYS

- FAULT TOLERANT - SELF TEST RECONFIGURABLE/REPAIRABLE ON STATION
- FAIL SAFE
- POWER OFF FOR LONG PERIODS OF TIME
- EXPERIMENT RELATED (HOL) PROGRAMS
- 300 - 1000 MBIT THROUGHPUT
- 10 G BYTE STORAGE

PROCESSOR SYSTEM BOGEYS/CAPABILITIES FOR DATA HANDLING AT LEVEL 4*

PERFORMANCE ESTIMATES	83	86	92
MOPS	10	10^3	10^6
STORAGE MBYTES	50	100	1000
TRANSFER RATES EXTERNAL MBITS/SEC	200	500	5000
TECHNOLOGY BASELINE			
A) TYPE	ECL	NMOS/CMOS	CMOS/GaAs/J.J.
B) DENSITY	VLSI	VHSIC I	VHSIC 2

VERY HIGH POWER BUDGET

VHSIC PROGRAM REVIEW

USING OPEN LITERATURE REFERENCES

11-116

DOD VHSIC PROGRAM

	GOALS	BUDGET
PHASE 1 MARCH-NOVEMBER 1980	DEVELOP DETAILED CONCEPTS AND PLANS NINE CONTRACTORS	$10.5 MILLION
PHASE 1 MAY 1981-APRIL 1984	DESIGN, DEVELOP, AND PILOT-PRODUCE 1 1/4 MICROMETER CHIPS WITH A 5×10^{11} GATE - Hz/cm^2 FUNCTIONAL THROUGHPUT RATE DEVELOP SUBSYSTEM BRASSBOARDS DEVELOP SUBMICROMETER CHIP TECHNOLOGY SIX CONTRACTORS	$167.8 MILLION
PHASE II 1984-86	DEMONSTRATE PHASE 1 BRASSBOARDS IN ACTUAL MILITARY APPLICATIONS DEVELOP AND PILOT-PRODUCE SUBMICROMETER CHIPS WITH 10^{13} GATE - Hz/cm^2 FUNCTIONAL THROUGHPUT RATE	$75 MILLION
PHASE III 1980-86	PROVIDE INNOVATIVE R&D IN SUPPORT OF PROGRAM GOALS WITH SOME 60 CONTRACTORS	$60 MILLION

SUMNEY, IEEE SPECTRUM DEC '82

VHSIC PHASE I ELEMENTS

CONTRACTOR (SERVICE)	TECHNOLOGY	BRASSBOARD	CHIP SET
HONEYWELL (AIR FORCE)	BIPOLAR ISL*, CML+	ELECTROOPTICAL SIGNAL PROCESSOR	PARALLEL PROGRAMMABLE PIPE-LINE CONTROLLER
HUGHES (ARMY)	CMOS ON SOS	ANTIJAM COMMUNICATIONS	DIGITAL CORRELATOR ALGEBRAIC ENCODER/DECODER SPREAD-SPECTRUM SUBSYSTEM
IBM (NAVY)	NMOS	ACOUSTIC SIGNAL PROCESSOR	COMPLEX MULTIPLIER/ACCUMULATOR
TEXAS INSTRUMENTS (ARMY)	BIPOLAR-STL++, NMOS	MULTIMODE FIRE-AND-FORGET MISSILE	DATA PROCESSOR ARRAY CONTROLLER AND SEQUENCER VECTOR ADDRESS GENERATOR VECTOR ARITHMETIC LOGIC UNIT STATIC RAM MULTIPATH SWITCH DEVICE INTERFACE UNIT GENERAL BUFFER UNIT
TRW (NAVY)	BIPOLAR-3D** TTL,CMOS	ELECTRONIC-WARFARE SIGNAL PROCESSOR	CONTENT ADDRESSABLE MEMORY WINDOW ADDRESSABLE MEMORY REGISTERED ARITHMETIC LOGIC UNIT ADDRESS GENERATOR MATRIX SWITCH 15-BIT MULTIPLIER/ACCUMULATOR MICROCONTROLLER FOUR-PORT MEMORY
WESTINGHOUSE (AIR FORCE)	BULK CMOS	ADVANCED TACTICAL RADAR PROCESSOR	PIPELINE ARITHMETIC UNIT EXTENDED ARITHMETIC UNIT CONTROLLER GATE ARRAY STATIC RAM

*INTEGRATED SCHOTTKY LOGIC +CURRENT MODE LOGIC ++SCHOTTKY TRANSISTOR LOGIC **TRIPLE DIFFUSION

SUMNEY, IEEE SPECTRUM DECEMBER 1982

VHSIC PHASE I ELEMENTS

CONTRACTOR (SERVICE)	DESIGN APPROACH	GATE DENSITY (GATES/MM^2)	GATE POWER (M W/GATE)	SPECIAL FEATURES
HONEYWELL (AIR FORCE)	CUSTOM CHIP-BASED MACROCELL LIBRARY	480	30	RADIATION HARDNESS RESPONSIVE GENERIC ARCHITECTURE
HUGHES (ARMY)	STANDARD & CUSTOM RECONFIGURABLE CHIPS	400	2	RADIATION HARDNESS ELECTRON-BEAM DIRECT-WRITE LITHOGRAPHY HIGHLY SPECIALIZED CHIPS
IBM (NAVY)	MASTER IMAGE WITH MACROCELL LIBRARY	570	100	SOFTWARE STRENGTH DESIGN APPROACH
TEXAS INSTRUMENTS (ARMY)	PROGRAMMABLE CHIP SET	390	37	OPERATIONAL FABRICATION FACILITY DESIGN UTILITY SYSTEM
TRW (NAVY)	STANDARD CHIP SET	TTL: 390 CMOS: 300	240 20	INNOVATIVE MEMORY CHIPS VERSATILE CHIP SET
WESTINGHOUSE (AIR FORCE)	STANDARD CHIP SET	1000	4	HIGHEST SPEEDS

SUMNEY, IEEE SPECTRUM DECEMBER 1982

OPTICAL MASS STORAGE SYSTEMS

GERALD M. CLAFFIE
RCA/GOVERNMENT SYSTEMS DIVISION/ADVANCED TECHNOLOGY LABORATORIES
MOORESTOWN, NEW JERSEY 08102

PRESENTED AT:

RENDEZVOUS AND PROXIMITY WORKSHOP
DATA SYSTEMS SESSION
NASA LYNDON B. JOHNSON SPACE CENTER
FEBRUARY 1985

11-120

#1

ARGON LASER BASED RECORDERS FOR GROUND PROCESSING
- HIGH DATA RATE
- HIGH DISK CAPACITY
- AUTOMATED DISK HANDLING

DIODE LASER BASED RECORDERS
- DIODE LASER ARRAYS FOR HIGH DATA RATE/HIGH CAPACITY

HIGH DATA RATE/HIGH CAPACITY DATA BUFFERS

RECORDING MEDIAL REQUIREMENTS

#2

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Key User Requirements — Argon Laser Based Recorders

REQUIREMENT	CURRENT/PAST	PROJECTED
CONTINUOUS DATA RATE (Mbps)	0-300	0->300
BEAMS/OPTICAL HEAD	9	9
DISK CAPACITY (BITS)	$\sim 10^{11}$	$\sim 5 \times 10^{11}$
14-INCH DIAMETER	-SINGLE SIDED	-DOUBLE SIDED
	-CAV RECORDING	-CLV RECORDING
READ BIT ERROR RATE	$< 10^{-9}$	$< 10^{-12}$
DATA ACCESS TIME (SECONDS)	<0.5	<0.25
FOR MOUNTED DISK		
ON-LINE DISK ACCESS (SECONDS)		
-WORST CASE (100 DISKS)	<6	<6
-DISK IN QUEUE POSITION	<3.5	<3.5
-FROM STORAGE LIBRARY	N/A	<15
OPERATING ENVIRONMENT	FIXED-BENEVOLENT	SAME

11-122

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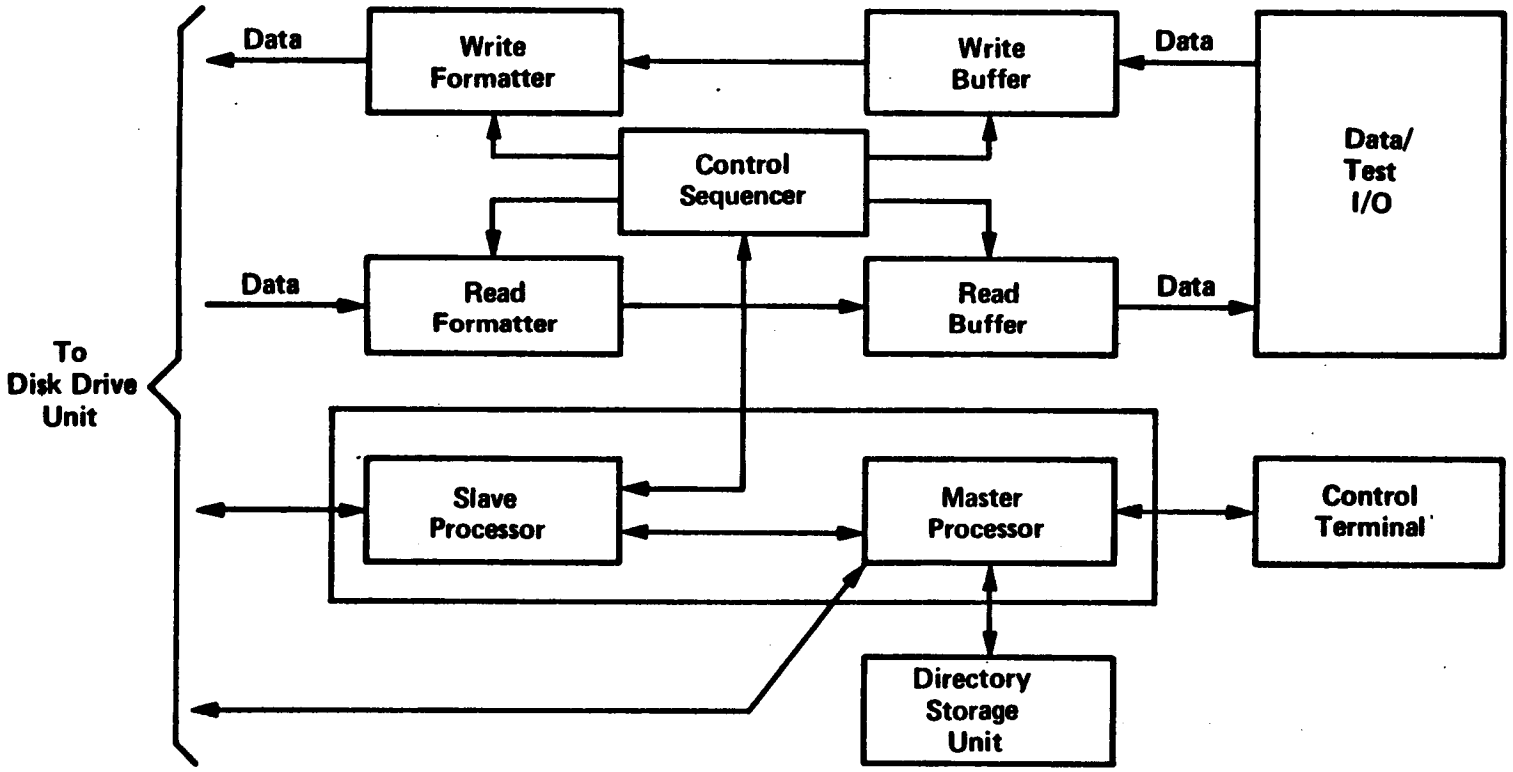
Controller



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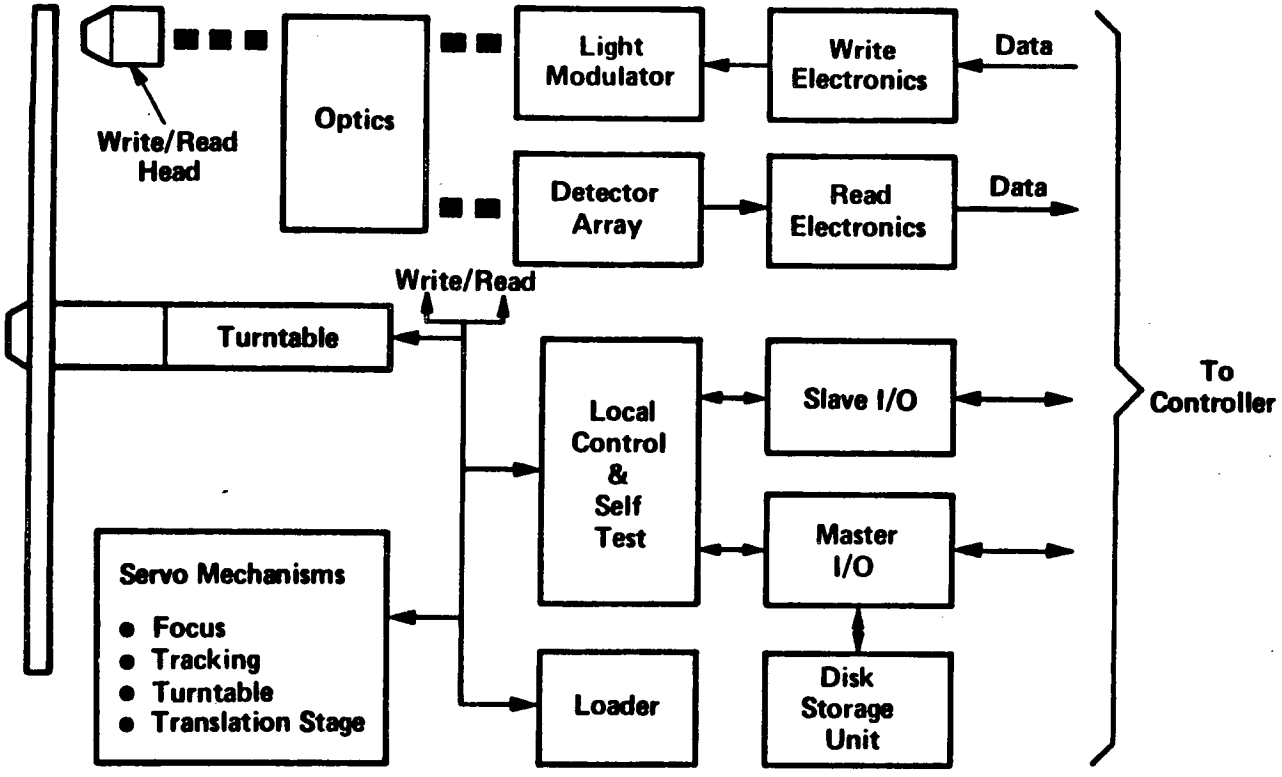
Disk Drive Unit



11-124

5

ORIGINALS FOR

Pages 11-125 Thru 11-127

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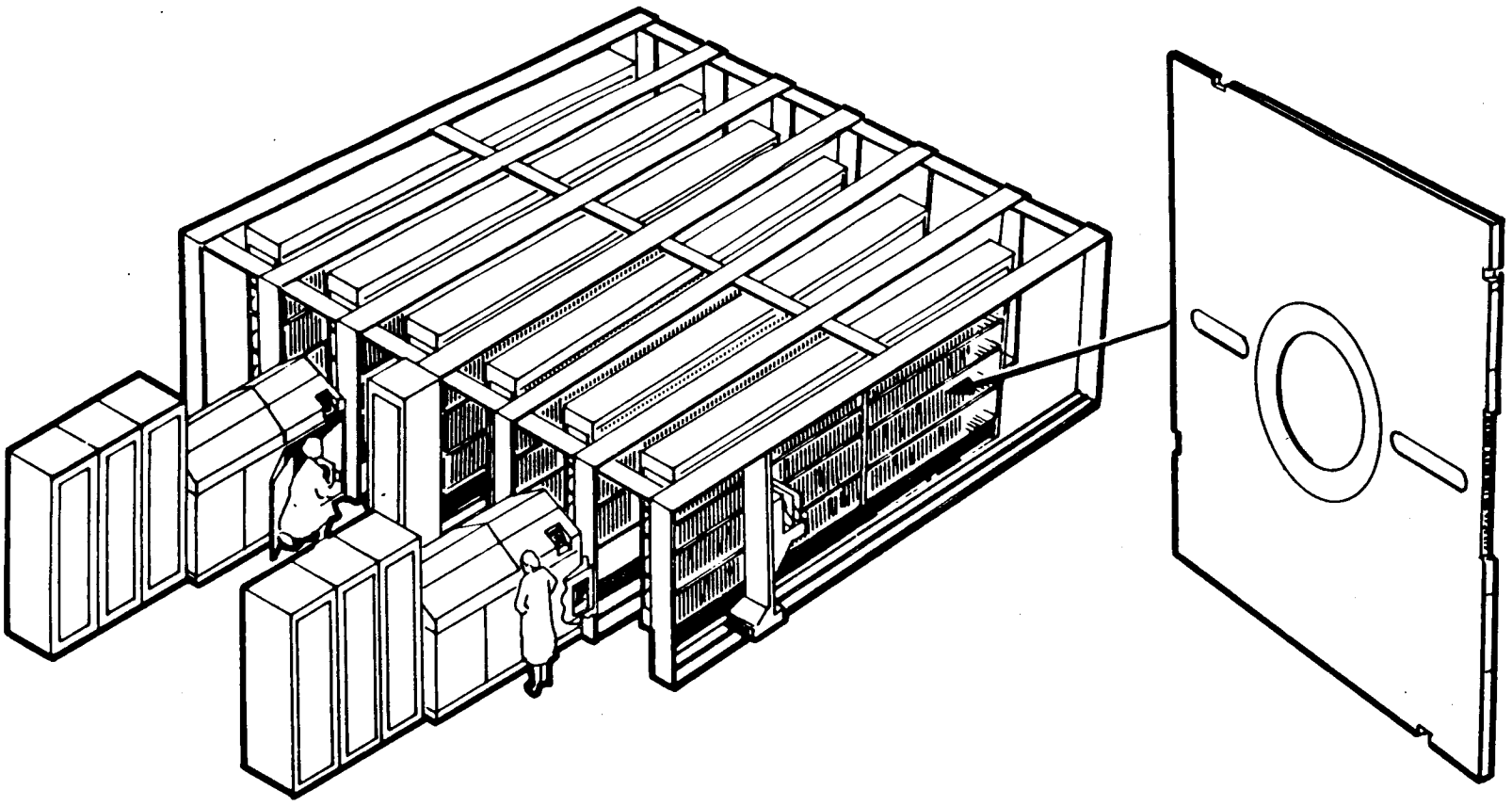
External Storage Library



11-128

RCA Advanced Technology Laboratories

Key User Requirements — Diode-Laser-Based Recorders

REQUIREMENT	CURRENT	PROJECTED
CONTINUOUS DATA RATE (Mbps)	0-20	0->100
BEAMS/OPTICAL HEAD	2	~10
DISK CAPACITY (BITS)	$(2-5)\times10^{10}$	$(1-2)\times10^{11}$
14-INCH DIAMETER	-SINGLE SIDED	-DOUBLE SIDED
	-CAV RECORDING	-CLV RECORDING
READ BIT ERROR RATE	$<10^{-8}$	$<10^{-12}$
DATA ACCESS TIME (SECONDS)	<0.5	<0.25
FOR MOUNTED DISK		
ON-LINE DISK ACCESS (SECONDS)		
-WORST CASE (100 DISKS)	<6	<6
-DISK IN QUEUE POSITION	<3.5	<3.5
-FROM STORAGE LIBRARY	N/A	<15
OPERATING ENVIRONMENT	GROUND/AIR	AIRCRAFT
	TRANSPORTABLE	SPACECRAFT
		OPERATIONAL

11-129

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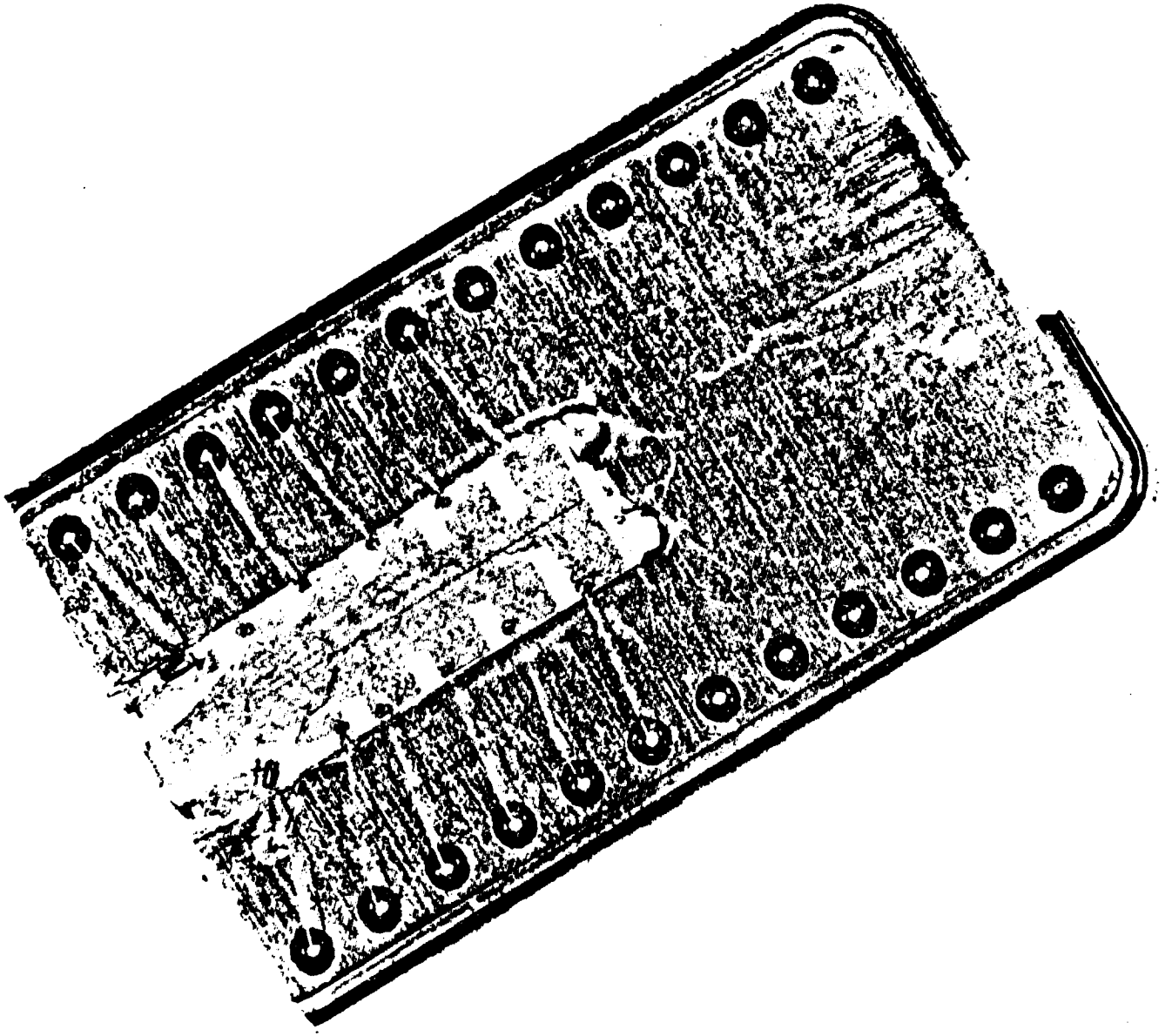
Monolithic Laser Diode Array

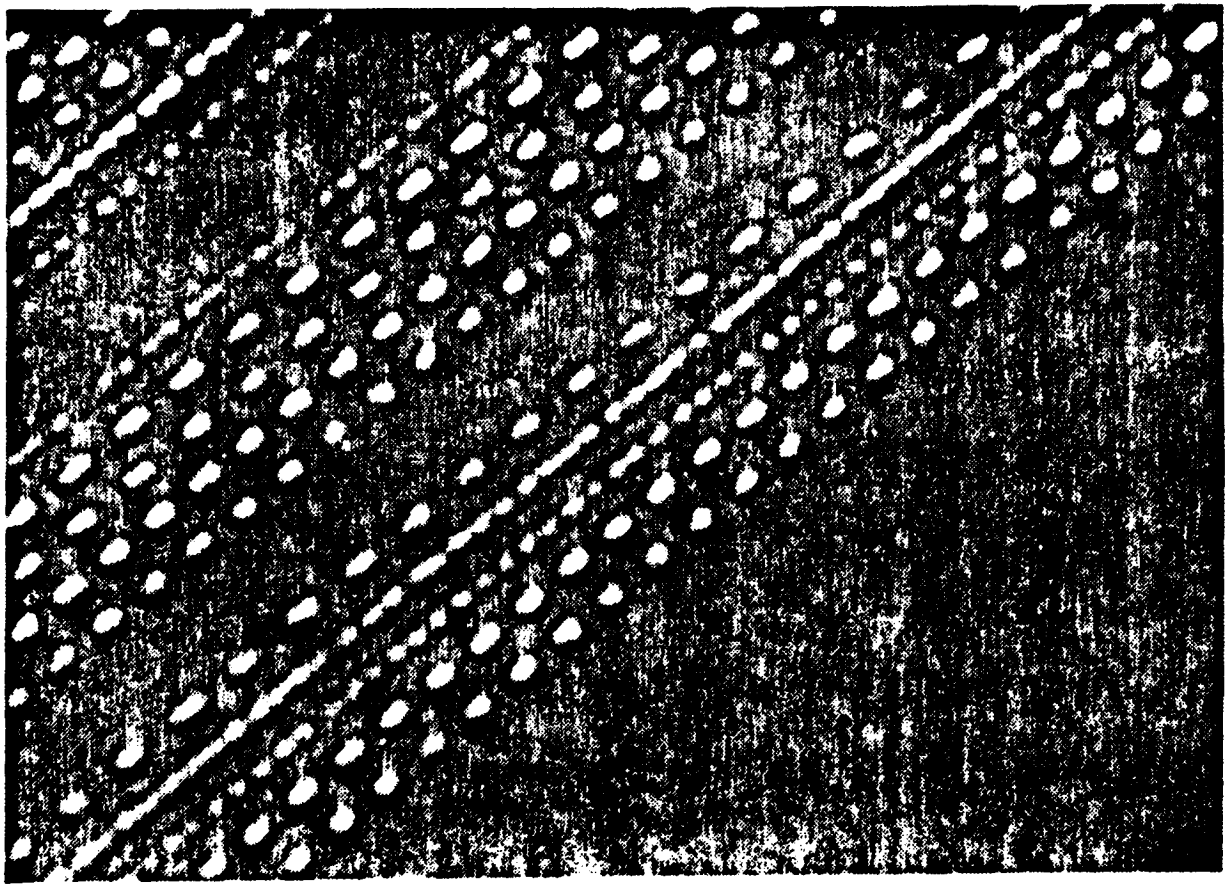


11-130

RC-C JOB NO. 94825 / NEG. ☒ POS. ☐ S/S ☒

11

Multitrack Recording



Multitrack Recording has been demonstrated by simultaneously recording 5-tracks from 5 adjacent diodes of the 10-diode array. As can be seen, the diodes were modulated separately with different signals. Ten-MHz, 12.5-MHz and 25-MHz square waves were recorded. Track-to-track spacing was 1.75 μm.

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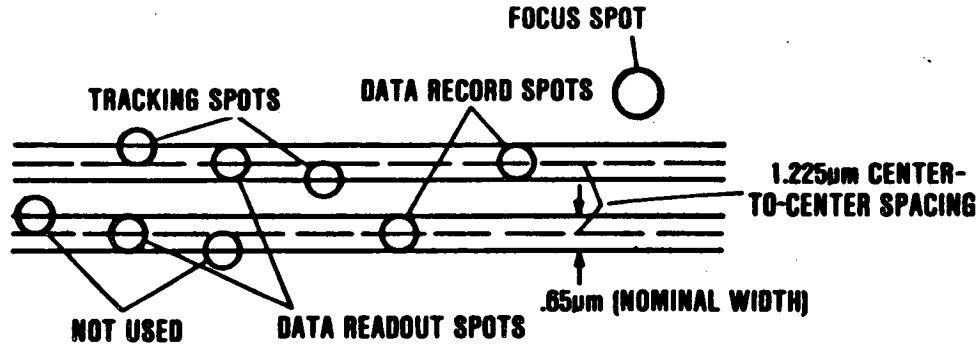
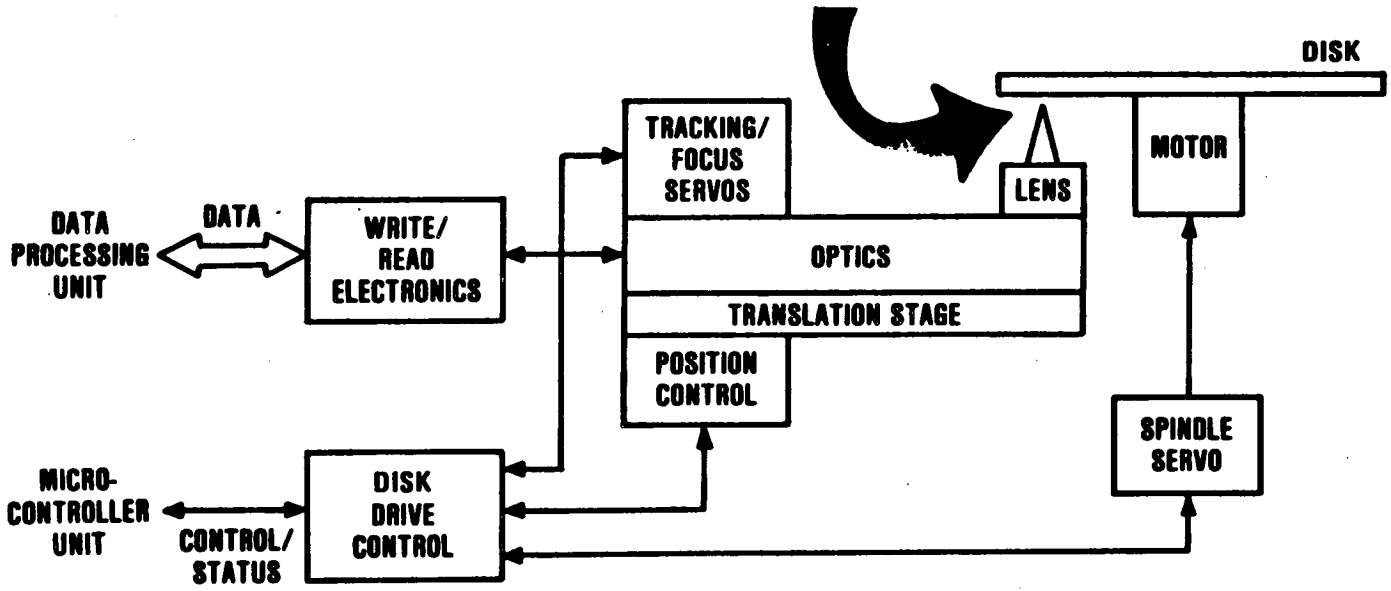
Disk Drive Unit (2 Laser Diodes)





11-132

13

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Summary of Recording Media Requirements

REQUIREMENT	CURRENT (ARGON/DIODE LASER)	PROJECTED
DISK DIAMETER (INCHES)	14	5.25-14
SUBSTRATE	WINCHESTER (ALUMINUM)	-ALUMINUM -FLEXIBLE
ROTATION RATE (RPM)	<3600	<3600
OPERATING WAVELENGTH (NM)		
-WRITE	488/820	488/<820
-READ	488/633	488/633/<820
-FOCUS	633	633
WRITE SPOT SIZE (μm)	0.4/0.65	0.4/0.65
WRITE/READ DATA RATE (Mbps)	<67	<100
DISK SENSITIVITY (mW)	5-15	5-15
-SURFACE LINEAL VELOCITY (900-1400 in/s)		
READ CARRIER-TO-NOISE RATIO (dB)	50-60	50-60
-22 MHz TONE/30 KHz BW		
READ BIT ERROR RATE (BER)	$<10^{-4}$	$<10^{-5}$
ARCHIVAL MEDIA LIFETIME (YEARS)		
-PRIOR TO USE	4	4
-AFTER USE	TBD	10-20
RESUABLE (ERASABLE) MEDIA	EVOLVING	YES

11-133

HIGH PERFORMANCE OPTICAL MASS STORAGE SYSTEMS ARE BEING DEVELOPED

- ENGINEERING MODEL ARGON LASER BASED JUKEBOX RECORDER HAS BEEN DELIVERED TO NASA-MSFC

  - ALTERNATE JUKEBOX CONFIGURATIONS AND DIODE LASER BASED RECORDERS ARE ALSO UNDER DEVELOPMENT
    - JUKEBOX CONFIGURATIONS
    - RUGGEDIZED SINGLE DISK RECORDERS
    - DIODE LASER ARRAYS FOR INCREASED DATA RATE

  - VERY HIGH DATA RATE/CAPACITY DIODE LASER ARRAY BASED BUFFER IS BEING DEVELOPED FOR USE WITH MAGNETO-OPTIC MEDIA

KEY RECORDER DEVELOPMENT GOALS

- COMPATIBILITY WITH EVOLVING PRODUCTION DISK MEDIA

- ADAPTABILITY TO VARIED HIGH PERFORMANCE USER REQUIREMENTS

#17

U.S. GOVERNMENT PRINTING OFFICE: 1985—569-014/20570

11-134