Center For Space Microelectronics Technology
And
Office Of Space Science And Instruments

SEMINAR

SPACE COMPUTING FOR THE YEAR 2000 AND BEYOND

University Of Illinois At Urbana-Champaign

By
Professor Ravi K. Iyer, Co-Director
Illinois Computer Laboratory For Aerospace Systems

And
Professor Prith Banerjee, Principal Investigator

Thursday, December 1 ,1988
10:00 A.M.
167 Conference Room

For Information Contact Carl Kukkonen (4-4814)

ORIGINAL PAGE IS
OF POOR QUALITY

Space-Borne Computing for the Year 2000 and Beyond

Ravi K. Iyer and Prith Banerjee
Computer Systems Group
Coordinated Science Laboratory
University of Illinois at Urbana-Champaign
Urbana, Illinois 61801

The influence and utilization of computers in space science investigations has greatly enhanced our ability to address difficult and complicated questions about our universe. Space science is wholly dependent on computers because the data acquired from instruments on the spacecraft are not only complicated in form but also voluminous. Although a great deal of attention has been paid to develop efficient and powerful computing systems on-ground, research in the area of spaceborne computing is far from satisfactory. On-board processing of data will be important in the future planetary missions where telemetry rates constrain the total amount of data which can be returned and many decisions may have to be made in real-time. Little thought has been given to a dynamic man-machine interface with regard to scientific real-time interactive control of flight experiments. Careful thinking is therefore essential to define appropriate spaceborne computing requirements for the future. We feel that it imperative that powerful multiprocessing systems for on-board processing be experimentally implemented and evaluated in selected application missions. The presentation will address key issues and attempt to define the requirements for such processing with some of NASA's future misions in perspective. The resulting architectural and performance issues and possible developments will also be addressed.

SPACEBORNE COMPUTING IN YEAR 2000

Ravi Iyer and Prith Banerjee

Illinois Computer Laboratory for Aerospace Systems
(NASA Center for Excellence)
Department of Electrical and Computer Engineering
University of Illinois at Urbana-Champaign

Acknowledgements: Some of the data and projections that will be presented today involve discussions with researchers at NASA-Langley, CS Draper Labs, Jet Propulsion Lab, and the Mission Adaptive Architecture research group at Univ. of Illinois. Others have been taken from SESAC Task Force, SIRTF Science Report-NASA-Ames, CADCOM Report.

SPACEBORNE COMPUTING IN THE YEAR 2000

PART I:

SPACEBORNE COMPUTING: OVERVIEW

Ravi Iyer, Co-Director

Illinois Computer Laboratory for Aerospace Systems and Software
(NASA Center for Excellence)
Department of Electrical and Computer Engineering
University of Illinois at Urbana-Champaign

OUTLINE

- Problems and Issues
- High Level Objectives
- On Board Processing on Past Missions
- Space Station Information Processing
- The Future

SPACEBORNE COMPUTING: PROBLEMS AND ISSUES

- Current Capabilities for On-Board Processing Insufficiently Understood

- Current On-Board Processing Architectures Inadequate for Future Control and Data Management Applications

- Long Delays Between Receipt of Data (On Ground) and Delivery of Pre-Processed Data to User (CADCOM Evaluation)

- Real-Time or Near Real-Time Response to Complex Events Inadequate

- Poor Man-Machine Interface for Flight Experiments

- Rapid Growth Rate of Spaceborne Data

- No Experimental Spaceborne Computing Environment

GOALS

- **On-Board Analysis**
  - ☐ Powerful Data Management System
  - ☐ High Scientific Return on Data
  - ☐ Real Time Observation of Various Scenarios (Image Processing and Pattern Recognition)
  - ☐ Interactive Payload Control to Allow Editing, Processing Based on Quality/Interest
- **On Board Command and Control**
  - ☐ Communication and Tracking
  - ☐ Guidance and Control
  - ☐ Fault Isolation, Recovery and Repair
  - ☐ Robotic and Expert System Services

ON-BOARD PROCESSING ON PAST SCIENCE MISSIONS

SUN-EARTH EXPLORER PROGRAM (ISEE)

- Limited to Various Modes of Filtering and Averaging
- Mode Selection Via Ground Commands
- Most Pre-Processing at IPD at Goddard

HIGH ENERGY ASTROPHYSICAL OBSERVATORY -2 (HEAO-2)

- Minimal On-Board Processing
- Individual Events Counted and Transmitted with Some Dedicated Hardware Analysis
- Low Data Rates (6.4 Kbps)

ON-BOARD PROCESSING ON PAST SCIENCE MISSIONS (cont'd)

VIKING MISSION TO MARS

- Several Scientific Instruments on Board (Orbiters and Landers)

- Low Data Transmission Rates (16 Kbps From Orbiters and 1 Kbps for Landers)

- Little On-Board Processing

  - ☐ On-Board Computers to Activate Specific Instruments

  - ☐ Lander Camera Control

  - ☐ Instrument Threshold Setting

ON-BOARD PROCSESSING ON PAST SCIENCE MISSIONS (cont'd)

SPACE TELESCOPE

- On-Board Target Acquisition
- Image Processing (Target Location)
- Telescope - Re-Positioning
- Averaging of Detector Readouts, Pulsar Signals and Exposure Meter Control
- Error Detection/Correction

SPACE STATION INFORMATION SYSTEM

- **Concept Definition**
  - ☐ Interconnected Processing Network
  - ☐ Flexible Interface Between Man and Space Environment
  - ☐ Nodes In Space and On Ground
  - ☐ Multiple Interactive Users
- **Objectives**
  - ☐ Interactive Command and Control of Space Elements
  - ☐ Support of Payload Tests and Core Function
  - ☐ Planned Growth of Computing and Automation Functions
  - ☐ High Reliability, Self-Test and Recovery Capabilities
  - ☐ Data Collection/Transmission

SPACE STATION: ON-BOARD COMPUTING AND DMS FUNCTIONS

FUNCTIONAL REQUIREMENT

- Real-Time Operations Management
- Multi-Processor Data Base Management System
- Extensive Status Monitoring
- On-Board Test/Verification
- Resource Management
- Global Fault Management/Recovery And Reconfiguration

SPACE STATION: OTHER FUNCTIONS

- Communication and Tracking
- Guidance, Navigation and Control
- Robotic Services

SPACE STATION: DATA-BASE MANAGEMENT SYSTEM

- **On-Board Multicomputer, Multiprocessing System**
  - ☐ Dual Environment
  - ☐ Command Control and Monitor Functions
  - ☐ Core and Payload Planning/Scheduling
  - ☐ Mass Storage Service
  - ☐ Telemetry Data Management Services
- **Hardware Resources**
  - ☐ Application and Communication Processors (4.0 MIPS, 4 Mbytes Memory, IO: 10 Mbps)
  - ☐ Mass Storage (172 MBytes, IO Rate: 1.25 MBytes/sec)
  - ☐ Data Acquisition and Distribution Components
  - ☐ Optical Token Ring Network

SPACE STATION: DATA-BASE MANAGEMENT SYSTEM (cont'd)

- **Software Resources**
  - ☐ Standard User Interfaces and Communication
  - ☐ OS Services
  - ☐ File and Data Base Management
- **Reliability**
  - ☐ Useful Life 30 Years
  - ☐ MTBF $40 \times 10^3 - 200 \times 10^3$ hours

THE FUTURE

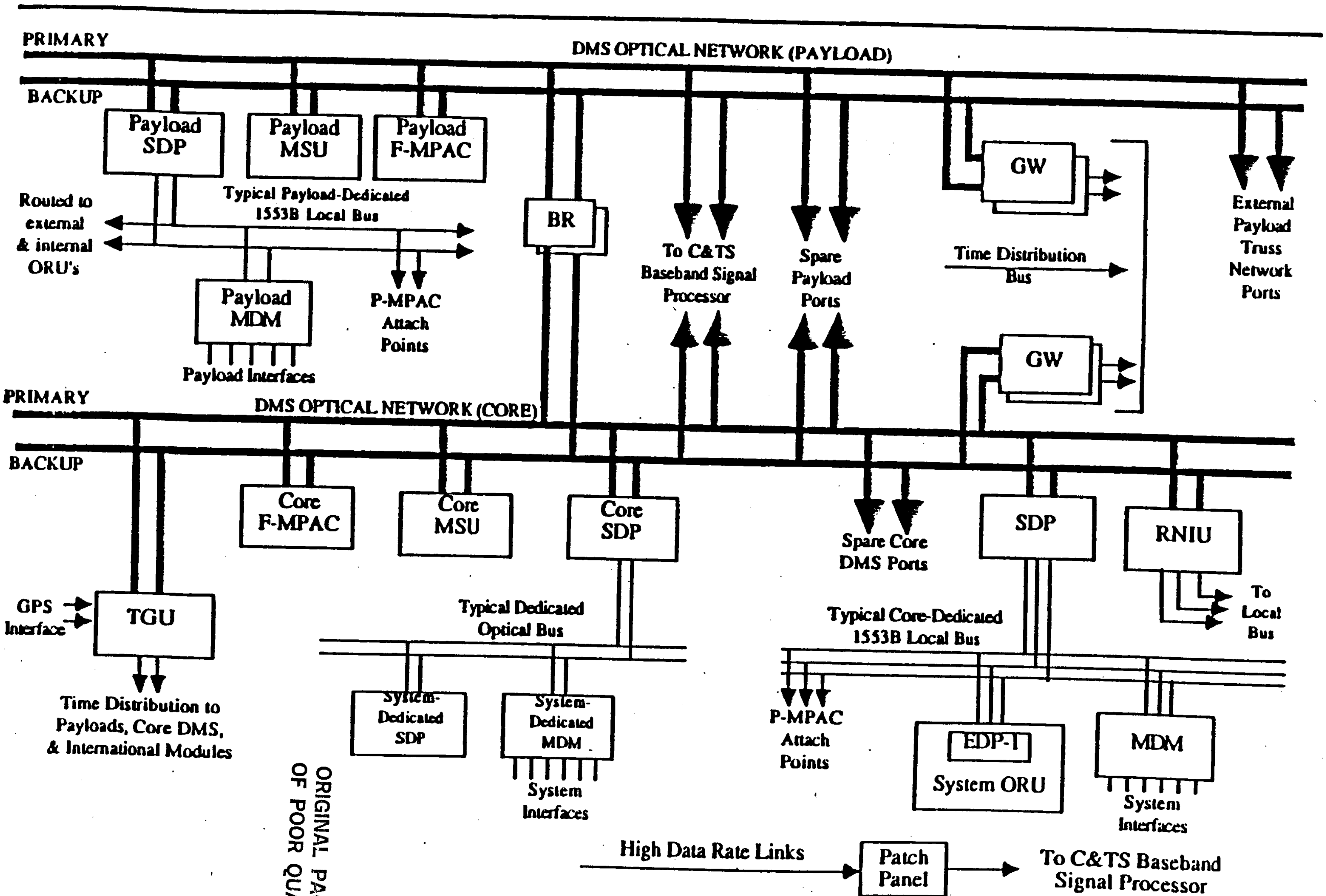
- Lunar Outpost
- Manned Mission to Mars
- Exploration of the Solar System

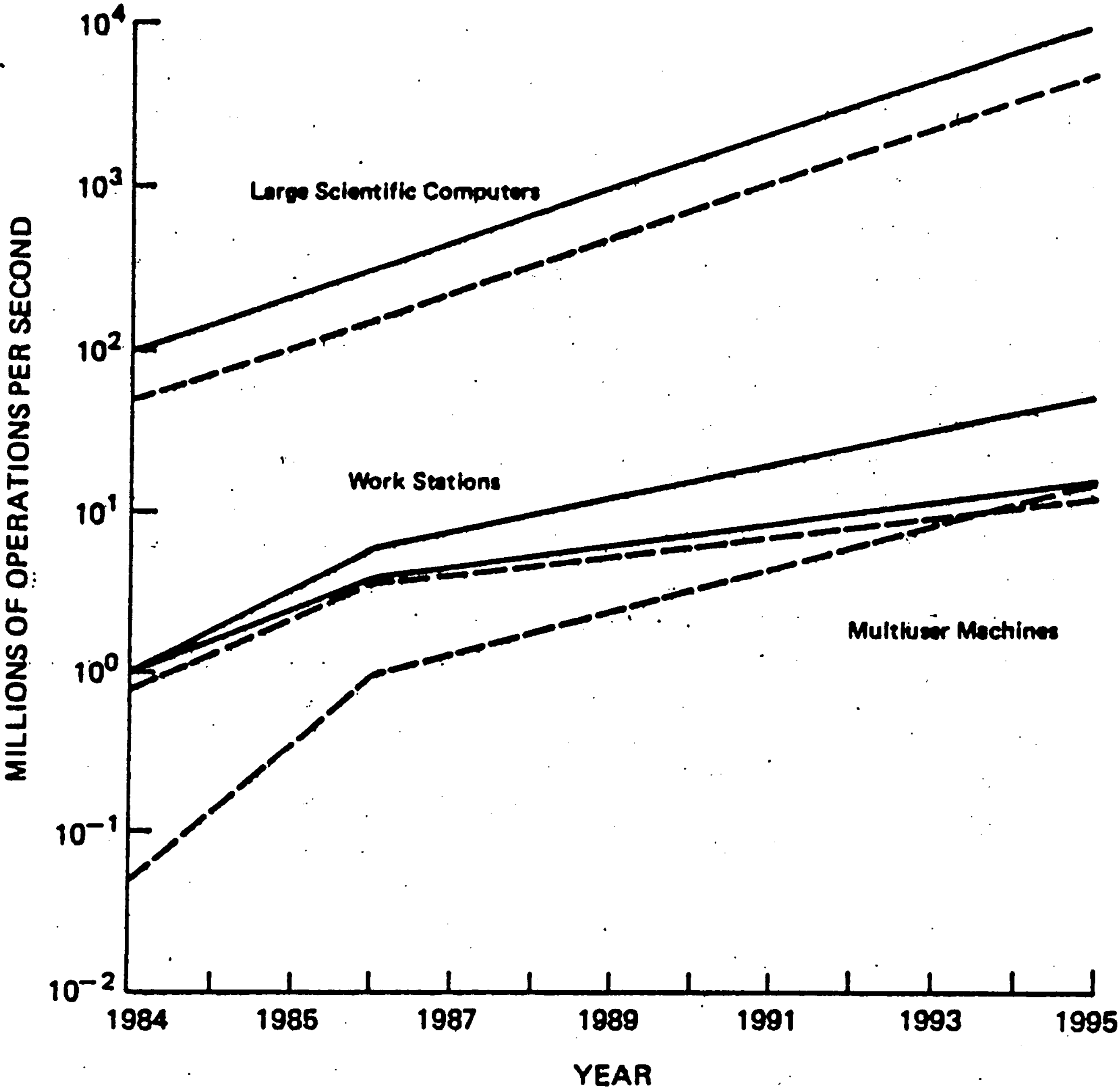
PROBLEMS (NEW AND OLD)

- Ability to Process and Deliver Enormous Quantities of Data
  - Multi-Instrument Multi-Disciplinary Investigations
  - Highly Variable Duty-Cycles
- Bounded Resources
  - Storage
  - Power
- Adaptive Mission Capability
  - Planned Changes in Scientific Scenarios
  - Unplanned Events/Missions
  - IO and CPU Bandwidth of Uniprocessors Clearly Inadequate
- New Approaches to High Performance, Dynamic and Adaptive Fault Tolerant Computing
- Experimental Testbed for Spaceborne High Performance Computing

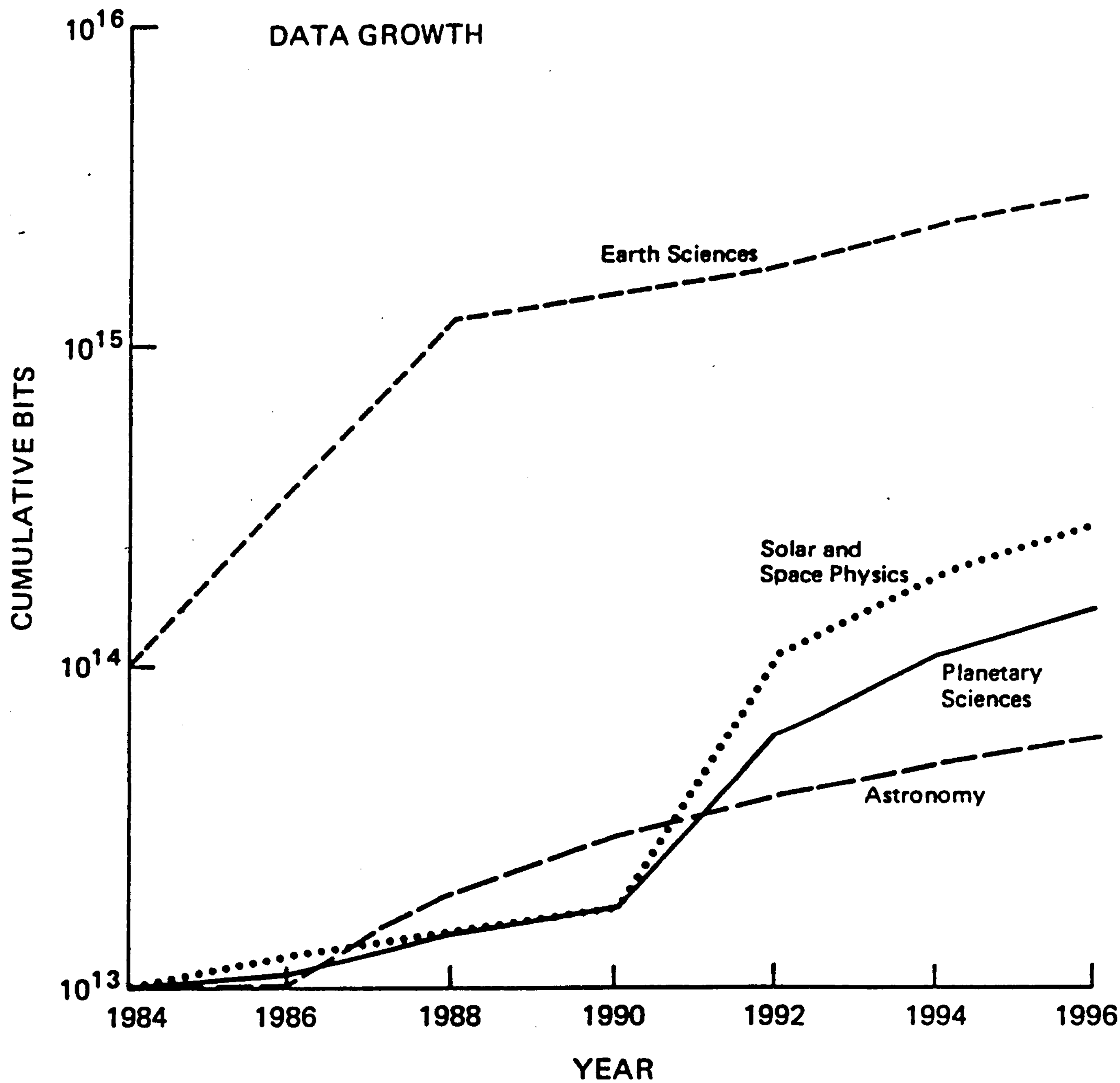
RESEARCH ISSUES

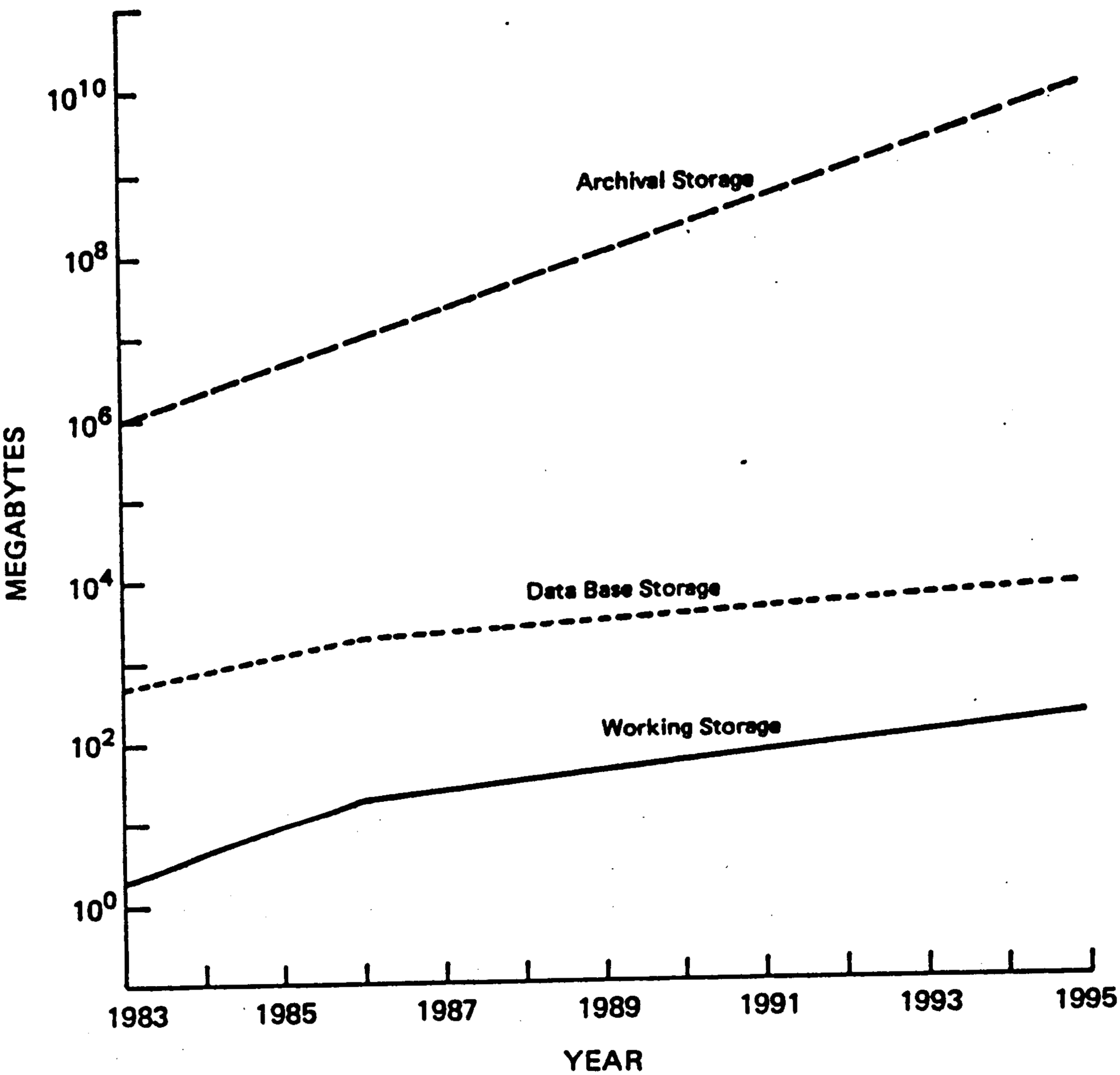
- New Innovative Approaches Needed to Meet the Complex Computing Needs of Future Space Missions
- Experimental Systems for Spaceborne Parallel Computing
- Explore Technology Issues for Computation and Data Management for Future (On-Board) Spaceborne Parallel Computers
- Develop Means for Searching, Selecting, Acquiring, and Processing a Wide Range of Data for Remote Space Experiments
- Develop On-Board and On-Ground Experimental Environments (Testbeds) for Validating Spaceborne Parallel Computing Methods and Technology
- Exploit Artificial Intelligence and Robotics for Deep Space Missions


PRIMARY
BACKUP
DMS OPTICAL NETWORK (PAYLOAD)
Payload SDP
Payload MSU
Payload F-MPAC
Routed to external & internal ORU's
Typical Payload-Dedicated 1553B Local Bus
Payload MDM
Payload Interfaces
P-MPAC Attach Points
BR
To C&TS Baseband Signal Processor
Spare Payload Ports
GW
GW
Time Distribution Bus
External Payload Truss Network Ports
PRIMARY
BACKUP
DMS OPTICAL NETWORK (CORE)
TGU
GPS Interface
Time Distribution to Payloads, Core DMS, & International Modules
Core F-MPAC
Core MSU
Core SDP
Typical Dedicated Optical Bus
System-Dedicated SDP
System-Dedicated MDM
System Interfaces
Spare Core DMS Ports
SDP
RNIU
To Local Bus
Typical Core-Dedicated 1553B Local Bus
P-MPAC Attach Points
EDP-I
System ORU
MDM
System Interfaces
High Data Rate Links
Patch Panel
To C&TS Baseband Signal Processor

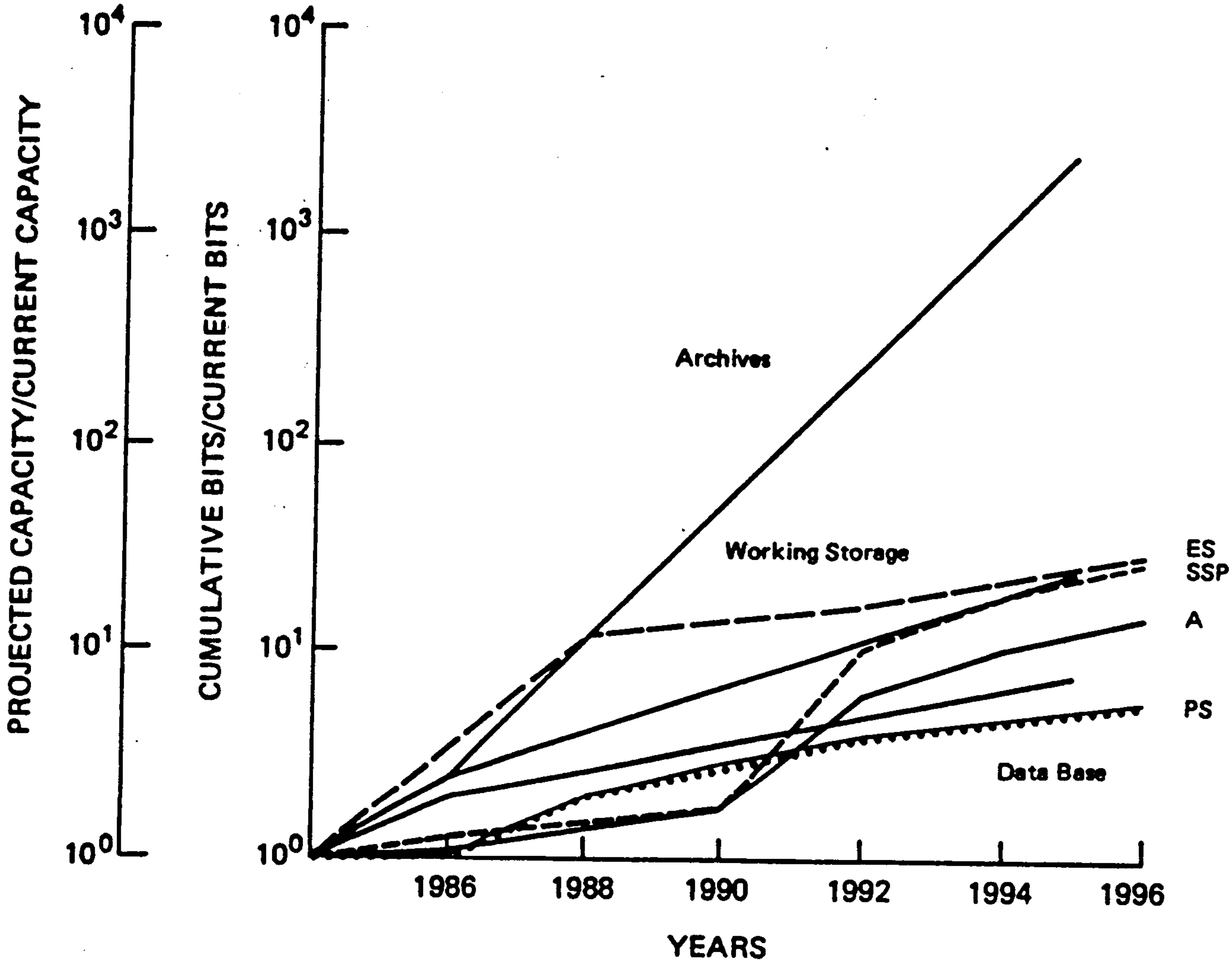


10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
MILLIONS OF OPERATIONS PER SECOND
Large Scientific Computers
Work Stations
Multiuser Machines
1984
1985
1987
1989
1991
1993
1995
YEAR


DATA GROWTH
CUMULATIVE BITS
10^{16}
10^{15}
10^{14}
10^{13}
Earth Sciences
Solar and
Space Physics
Planetary
Sciences
Astronomy
1984
1986
1988
1990
1992
1994
1996
YEAR



Archival Storage
Data Base Storage
Working Storage
MEGABYTES
10^{10}
10^8
10^6
10^4
10^2
10^0
1983
1985
1987
1989
1991
1993
1995
YEAR



PROJECTED CAPACITY/CURRENT CAPACITY
CUMULATIVE BITS/CURRENT BITS
10⁴
10³
10²
10¹
10⁰
Archives
Working Storage
ES
SSP
A
PS
Data Base
1986
1988
1990
1992
1994
1996
YEARS

SPACEBORNE COMPUTING IN THE YEAR 2000

PART II:

ARCHITECTURAL REQUIREMENTS

Prith Banerjee, Principal Investigator

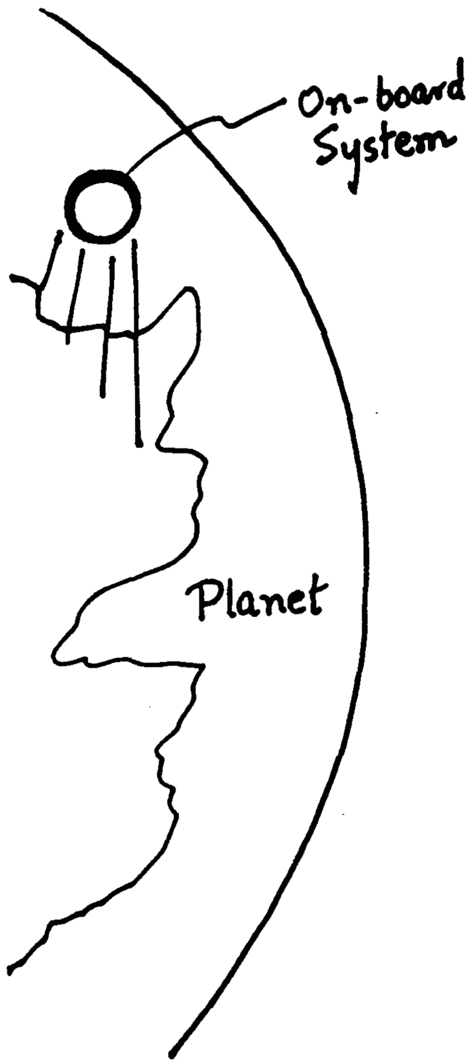
Illinois Computer Laboratory for Aerospace Systems and Software
(NASA Center for Excellence)
Department of Electrical and Computer Engineering
University of Illinois at Urbana-Champaign

Outline

- Possible applications and computational requirements
- Reliability, adaptiveness and reconfigurability requirements
- Architectural choices and directions
- Research issues
- Conclusions

Objective of an On-Board Information System

- To provide an optimal, adaptive computational resource for diverse applications demanded by space/planetary exploration



FUNCTIONS

- Navigation/Guidance
- Control
- Communications
- Scientific Data Analysis
- Imaging
- Expert Advisor
- Data Management

Possible Applications and Computational Requirements

(1) **Navigation/guidance**: get sensor data, and *reliably* perform operation in *real-time*, activate controls

- ☐ Typical requirements: 5-50 MIPS, 10^{-6} to 10^{-8} failures per hour
- ☐ Examples of NASA sponsored projects: SIFT at SRI International, FTMP at CS Draper for aircraft control in mid-1970s
- ☐ More current NASA projects: AIPS and FTPP at CS Draper Labs in 1980s
- ☐ Performance-reliability figures of existing computers

Prob (Failure, per hour)

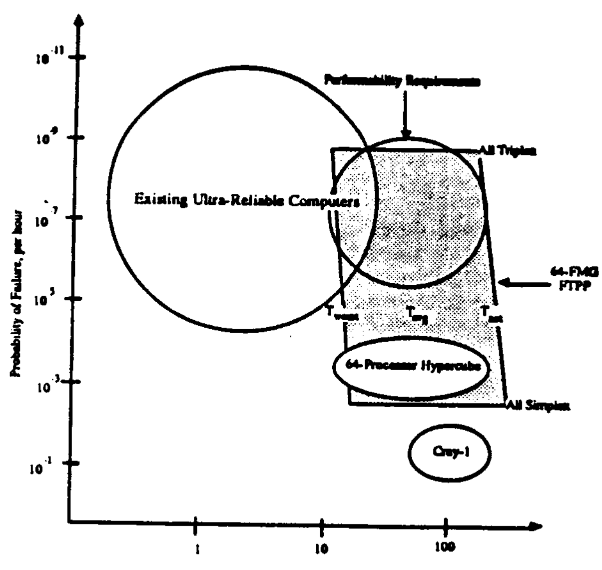


Figure 1. Performability Diagram

Throughput, MIPS

Possible Applications and Computational Requirements (Cont'd)

(2) **Communications:** Telemetry with fast encoding/decoding of scientific data collected on board to earth station (projected at 10-100 GB/sec in CADCOM report)

- Example bandwidth requirements: 120 Million complex words/sec on Canadian Radarsat satellite for SAR Radar data => would need 1 GByte/sec capacity

(3) **Scientific Data Analysis:** algorithms for running space experiments and analyzing data and modifying data collection if possible

- Might need anywhere around 1 GFLOPS of computational power

Possible Applications and Computational Requirements (Cont'd)

(4) **Real-time Signal Processing**: for tracking various objects in space, surveillance systems, needing matrix operations and linear algebra operations, beamforming, heterodyning, filtering

- Example computational capabilities:

  (a) SAXPY-1M systolic processor uses 32 processors in linear array to achieve 1 GFLOPS.

  (b) Motorola T-ASP array processor uses 8 processors to sustain 0.4 GFLOPS

(5) **Real-time Image Processing**: needed for seismic surveys on a surface of a planet and new imaging techniques require 2D FFT, 2D convolution, zero crossings, feature matching, depth computation, filtering of patches, clustering, connected component labeling, median filtering, Hough transform

- Example computational requirements:

  CMU WARP programmable systolic processor has 10 processors in array delivering 100 MFLOPS

Possible Applications and Computational Requirements (Cont'd)

(6) **Problem Manager (Expert system)**: AI and logic operations to build an expert or learning system to respond to unknown environments in real-time

- Computational requirements around 100 Million LIPS

(7) **Database Management System**: Data storage requirements for onboard systems are more than current since data not sent to Earth

- Projected at 10-100 GBytes of storage from CADCOM report

Other Requirements of On-Board Information System

- Needs to be autonomous for periods up to 30-50 years
- Certain key elements require fault tolerance with a reliability of 0.95-0.99 over a 30-50 year period
- Possibly real-time application, hence real-time software
- Power-weight limitations
- Adaptive and reconfigurable to various unknown conditions

Adaptiveness and Reconfigurability Requirements

- Adaptiveness to meet different functional requirements during mission
- Adaptiveness to change in operating conditions
- Adaptiveness to support different modes of operations in scientific experiments
- Adaptiveness to meet the unexpected in exploration
- Adaptiveness to failures

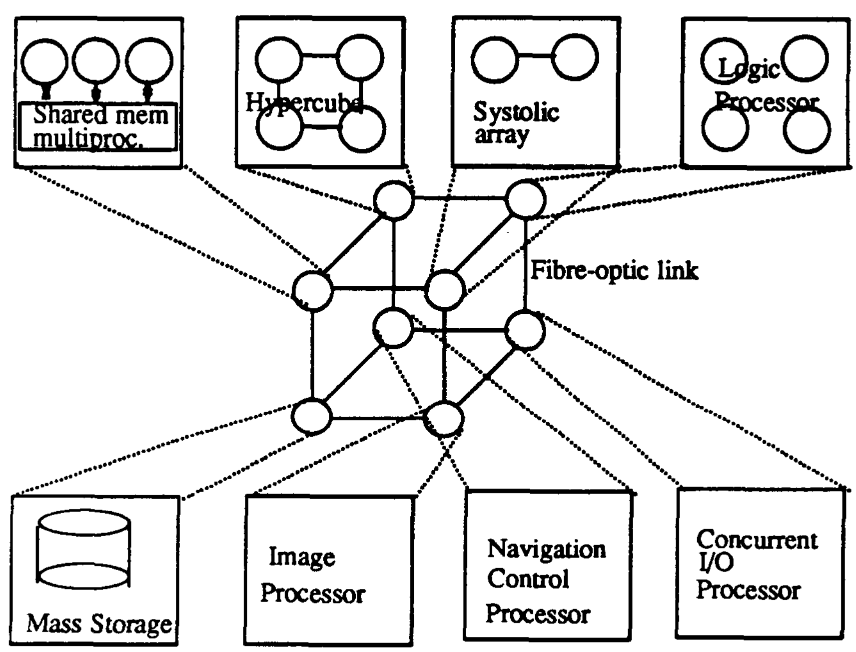
History/Projections of Medium-Grain Computers

Generation Years	First 1983-87	Second 1988-92	Third 1993-97
Typical Node			
MIPS	1	10	100
MFLOPS scalar	0.1	2	40
MFLOPS vector	10	40	200
memory (Mbytes)	0.5	4	32
Typical system			
N (nodes)	64	256	1024
MIPS	64	2560	100K
MFLOPS scalar	6.4	512	40K
MFLOPS vector	640	10K	200K
memory (MBytes)	32	1K	32K
Communication latency (100 byte message)			
neighbor(microsec)	2000	5	0.5
nonlocal(microsec)	6000	5	0.5

- By late 1990s, the hardware will be ready to offer 40-50 GFLOPS of performance using 1000 processors

A Possible Architecture

- Required to deliver large computational power (10-100 GFLOPS) for specific operations, lower in others -> characterized as *long poles*
- A network of heterogeneous nodes connected by high-speed fibre-optic links
- Using some interconnection topology (e.g. hypercube), with fault tolerant routing



Features of Proposed Architecture

- Different tasks have different node architectures for best operation -> some need vector processing, others systolic processing, others shared memory parallelism, etc.
- Special-purpose computations performed on specialized nodes, e.g. array processors -> since 10-100 GFLOPS difficult to achieve on general purpose parallel processor
- Use general purpose parallel processor for other tasks for greater throughput
- Every node is highly reliable (has some degree of fault tolerance)
- Every node has one or more other nodes that can perform its task in case of failure (possibly in degraded mode) -> No single point of failure
- Need very fast communication, adaptive routing -> hyperswitch technology developed at JPL is very useful

Research Issues

- **Processor architecture:**
  - ☐ Gallium arsenide technology for radiation-hardened?
  - ☐ Redundancy in processors
  - ☐ Combination of both?
  - ☐ Grain size - coarse grain, fine grain
- **Memory architecture:**
  - ☐ Shared or distributed memory for parallel organizations, or mixed?
  - ☐ Hierarchy of memory organizations, virtual memory?
  - ☐ Redundancy or radiation hardened technology, or both?
- **Communications:**
  - ☐ Fibre-optic links using Waveform Division Multiplexing -> all glass passive interconnect, fault tolerant, high data rate
  - ☐ Interconnection topology?
  - ☐ Adaptive routing -> hyperswitch?

Research Issues (Cont'd)

- **Mass Storage**
  - Low power, weight restrictions
  - Optical disks?
  - Multiple disks for higher reliability and for higher performance (concurrent I/O)
- **Software**
  - Distributed operating systems
  - Real-time operating systems
  - Software fault tolerance
  - Software engineering
- **Fault tolerance issues:**
  - HARDWARE: Fault detection and error masking in hardware: Byzantine voting approach, or duplication and comparison in hardware
  - SOFTWARE: Fault isolation and reconfiguration, recovery
  - Use of fault-tolerant building blocks, e.g. FTPP quad redundant blocks
  - Use of hierarchical fault tolerance

Conclusions

- On-board Information System for Spaceborne computing has high computational and reliability requirements
- Feasible in the future (Year 2000 and beyond)
- Need massively parallel processing with power-weight limitations

What is Needed to Accomplish Objective

- A NASA-wide evolutionary laboratory or testbed for evaluating/ investigating possible choices of architectures for On-Board Information Systems
- Evaluate and quantify system level performance and reliablity issues
- Evaluate competing technology approaches
- Develop techniques for rapid prototyping for proof-of-concept implementations
- Develop Design/Validation/Simulation tools that permit rapid prototyping of real-time systems from a given set of requirements

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS None
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) UILU-ENG-88-2265 (CSG-95)	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Coordinated Science Lab University of Illinois 6b. OFFICE SYMBOL (If applicable) N/A	7a. NAME OF MONITORING ORGANIZATION National Aeronautics and Space Administration
6c. ADDRESS (City, State, and ZIP Code) 1101 W. Springfield Avenue Urbana, IL 61801	7b. ADDRESS (City, State, and ZIP Code) NASA Langley Research Center Hampton, VA 23665
8a. NAME OF FUNDING/SPONSORING ORGANIZATION National Aeornautics & Space Admin. 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER NASA: NAG 1-613
8c. ADDRESS (City, State, and ZIP Code) See block 7b	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
Space-Borne Computing for the Year 2000 and Beyond

12. PERSONAL AUTHOR(S)
Ravi K. Iyer and Prith Banerjee

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Technical	FROM ______ TO ______	December 1988	38

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Space-borne computing, parallel processing, reliability, performance, storage, future NASA missions.

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The influence and utilization of computers in space science investigations has greatly enhanced our ability to address difficult and complicated questions about our universe. Space science is wholly dependent on computers because the data acquired from instruments on the spacecraft are not only complicated in form but also voluminous. Although a great deal of attention has been paid to develop efficient and powerful computing systems on-ground, research in the area of spaceborne computing is far from satisfactory. On-board processing of data will be important in the future planetary missions where telemetry rates constrain the total amount of data which can be returned and many decisions may have to be made in real-time. Little thought has been given to a dynamic man-machine interface with regard to scientific real-time interactive control of flight experiments. Careful thinking is therefore essential to define appropriate spaceborne computing requirements for

(Continued)

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code) / 22c. OFFICE SYMBOL

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

the future. We feel that it imperative that powerful multiprocessing systems for on-board processing be experimentally implemented and evaluated in selected application missions. The presentation will address key issues and attempt to define the requirements for such processing with some of NASA's future misions in perspective. The resulting architectural and performance issues and possible developments will also be addressed.