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OPTICAL MEMORY APPLICATION ASSESSMENT

Boeing Defense & Space Group

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13. ABSTRACT (Maximum 200 words)

Optical memory technology affords the promise of faster, more compact and larger capacity storage capabilities for high performance computing requirements. Many military programs have such requirements and development of this technology will be critical to accomplishing these goals. In the development of optical memory technology, certain tradeoffs will be required among various system parameters such as capacity and access time. In order the maximize the utility of this technology, the development must be planned and prioritized to foresee these tradeoffs in the optimum way. Under this effort, 3-D optical memory technology was reviewed and compared with other competing storage technologies. In addition, ground, airborne and space military applications were reviewed and system requirements identified. A technology roadmap to guide future developments was created.

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List of Acronyms

AST	Airborne Surveillance Testbed
ATIMS	Airborne Tactical Information Management System
ATM	Air Traffic Management
AVTR	Airborne Video Tape Recorder
AWACS	Airborne Warning and Control System
BER	Bit Error Rate
CBT	Computer Based Training
CCD	Charge Coupled Device
CD	Compact Disc
CONV-HAE	Conventional High Altitude Endurance
COTS	Commercial Off the Shelf System
CPU	Central Processing Unit
CW	Continuous Wave
DARO	Defense Airborne Reconnaissance Office
DAU	Data Acquisition Unit
DCW	Digital Chart of the World
DEMPC	Data Exploitation Mission Planning and Communications
DMA	Defense Mapping Agency
DMA	Defense Mapping Agency
DNA	Deoxyribonucleic Acid
DoD	Department of Defense
DRAM	Dynamic Random Access Memory
DTED	Digital Terrain Elevation Data
DVD	Digital Versatile Disk
E&MD	Engineering and Manufacturing Development
ECIT	Electronic Combat Integrated Test
EMI	Electromagnetic Interference
FAA	Federal Aviation Administration
Gbps	Gigabits per second
GBps	Gigabytes per second
HDSS	Holographic Data Storage System
HUD	Heads Up Display
I/O	Input/Output
ISDN	Integrated Services Data Network
JPEG	Joint Photographic Experts Group
JSF	Joint Strike Fighter
KBps	Kilobytes per second
LAN	Local Area Network
LO-HAE	Low Observable High Altitude Endurance
MAE	Medium Altitude Endurance

Mbps	Megabits per second
MBps	Megabytes per second
MPEG	Motion Pictures Experts Group
NATO	North Atlantic Treaty Organization
PI	Parallel Interconnect
OSA	Open System Architecture
PMA	Portable Maintenance Aid
PRISM	Photorefractive Information Storage Materials
RAID	Redundant Arrays of Inexpensive Disks
RAM	Random Access Memory
ROM	Read Only Memory
SAMCOMS	Special Air Missions Communications Systems
SEM-E	Standard Electronic Module Type E
SLM	Spatial Light Modulator
SPOT	Système Probatoire d'Observation de la Terre
STOVL	Short Takeoff/Vertical Landing
UAV	Unmanned Autonomous Vehicle
WAN	Wide Area Network
WORM	Write Once Read Many

Executive Summary

Current and future military programs in the areas of surveillance, reconnaissance and intelligence have increasing need to gather, assimilate and analyze large amounts of data. These requirements stem from both ground-based applications such as battlefield situational awareness, mission logistics, and intelligence data and airborne requirements such as avionics, requirements for in-flight diagnostics, and on-board maintenance, as well as mission-specific requirements. Among specific types of memory intensive applications are those that require image analysis, or use sensors with very wide bandwidths and high speed data buses.

It is generally recognized that currently available memory systems will not fulfill all the needs of future systems. Development must begin now for insertion into new systems over the next decade. Promising new technologies include optical holographic and two-photon memory systems. Rome Labs is sponsoring development of these types of systems and to assist in this development an analysis of the storage needs of various military and commercial programs was performed.

The programs studied consisted of commercial and military programs in the Boeing Company. These included both ground-based and airborne systems. Among the ground-based systems were Computer Based Training, mission planning applications and Air Traffic Management. Among the airborne systems were B-1B, F-22, JSF, UAV's and commercial flight test. For each of these programs, data was gathered reflecting their mission need requirements for mass storage. Projections were made for requirements out through the next decade. Using these requirements, together with an assessment of the current state of two-photon memory technology, a roadmap toward insertion of this technology into fieldable, useful systems is presented.

1.0 Introduction

Current and future military programs in the areas of surveillance, reconnaissance and intelligence have increasing need to gather, assimilate and analyze large amounts of data. These requirements stem from both ground-based applications such as battlefield situational awareness, mission logistics, and intelligence data and airborne requirements such as avionics, requirements for in-flight diagnostics, and on-board maintenance, as well as mission-specific requirements. Among specific types of memory intensive applications are those that require image analysis, or use sensors with very wide bandwidths and high speed data buses.

It is generally recognized that optical memories afford the promise of faster access times, large storage amounts in small volumes and larger data throughput rates for mass data storage. This is driving much research effort in the areas of materials, system architectures, and optical interconnection schemes. In the development of these technologies, critical tradeoffs are being made between system capabilities. As an example, in most systems, there is a direct tradeoff between storage capacity and access rate. In order to focus the development efforts, information regarding current and projected system requirements for specific military programs is required. This report presents results of a study of such requirements for storage technology for a variety of military and commercial systems within the Boeing Company. The programs selected include both ground-based and airborne systems. The ground-based systems include such varying applications as Computer Based Training and mission planning stations for military aircraft. Airborne systems consist of commercial and military jets including bombers, fighters and unmanned aircraft. In performing this study we have first examined the state of the art in storage technologies and the progress of these technologies. Using this information, we have presented to a number of program personnel the promise of better performance. They have expressed to us their view of their needs for the next decade in terms of storage requirements. Not all the personnel interviewed anticipate a need for better performance; some have adequate technology now for all they will need. Some programs were unable to divulge any pertinent information due to competition sensitivity or proprietary concerns or because of classified information. Using the information derived from the programs, plus information from Call/Recall, Inc. which is developing storage technology under contract from the Air Force Rome Laboratory, we have created a technology roadmap for the development of two-photon memory technology. The goal from this roadmap is to develop fieldable systems that will ultimately be inserted in military programs.

To summarize our analysis, we follow the following format. We begin with a tutorial on types of memory and current performance levels. These include electronic, magnetic and optical based. Optical types include both bit-wise planar and volume technologies as well as volume holographic. We concentrate on two-photon volume systems for this assessment. Following the technology summaries, we present the programs examined. For each we include a discussion of their mission objectives and current state as well as projected requirements over the next decade. We begin with programs using ground-based systems and continue to airborne ones. After reviewing all the programs surveyed, and the requirements drawn from them, we present a roadmap proposing the path needed to take the technology from today's state to the required state of the next decade. We then include a list of additional programs worthy of consideration for memory requirements or as potential customers to serve as field test programs. Due to limitation of funds and time, these programs were not studied in the current contract, but have the potential to be useful. The report concludes with a summary and is followed with an appendix listing programs that were initially evaluated but not deemed suitable for presentation in the study.

1.1 Methodology

The study reported here consists of two principal tasks. The first was a technology requirements assessment. This consisted of a survey of the current field in storage technology. This was accomplished mainly by standard traditional methods using published articles in technical and trade journals. A second part of task I was to survey promising, appropriate programs with needs in this area and then determine their current status and future needs. Due to the nature of the information being gathered, this task was performed mainly via personal interviews. Programs were first selected in a broad overview of the military and commercial parts of the Boeing Company. Promising candidate programs were chosen and appropriate personnel contacted. In many instances all the contact was done and information transferred via telephone calls. In very few cases was there any written information available discussing the needs of the programs. For this reason, it was necessary to try to draw on the vast experience of the cumulative whole of various programs. Due to the nature of military contract work, often program personnel do not have the luxury of looking beyond immediate contracted requirements. Often, coaxing people to project requirements in the future proved difficult as people were reluctant to speculate. Sometimes there were contradictory estimates from personnel on the same program. In the course of this contract we tried a number of techniques to try to persuade people to be forthcoming with projected requirements. This included telephone interviews, personal interviews and mailed surveys. The most effective means of obtaining the required information was by personal interviews. Often people's initial reaction was "Our program has no need and will not ever need anything like that"; but if given the opportunity to talk about the technology and listen to the possibilities, they could frequently come up with desirable requirements. The trick seemed to be persuading people to spend enough time to be comfortable with the concept. Charts illustrating some real hardware, i.e., the Call/Recall ROM demonstration system, helped people believe in the technology.

In addition to information on specific programs obtained from program personnel, another general source of information was the Boeing Defense & Space Group Concepts and Analysis organization. This organization looks at a very broad picture for defining future company business. Hence, they need to look at the big picture and the long term picture. In this sense they need to be aware of new technology developments as well as new and future customer (either commercial, civilian or military) interests. This group has the directive to look way out and assess high risk technologies and systems.

A final nontraditional source of data is the World Wide Web portion of the Internet. This vast collection of computer files contains a wealth of information. In particular, for unclassified military programs it was very useful. Often people intimately involved in the program forget the broad picture and this resource proved very useful for getting program mission summaries. Where this information resource has been useful, it is mentioned in the text.

The second task was to develop a technology roadmap for the development of two-photon storage systems into a fieldable technology. This plan is based on the study of the technology as it now stands, interactions with personnel from Call/Recall, Inc., primary requirements for existing programs obtained in Task I, and the development of auxiliary technology. Interactions with Call/Recall, Inc. personnel included a trip to their facilities to observe the current state of their progress in developing two-photon optical storage. The goal of the roadmap is to present a direction and prioritize the paths of technology development and transfer and plan for insertion into current and future systems.

2. 0 Review of Storage Technologies

In this section, we review the current state of computer storage technology. This technology includes solid-state (mostly silicon) devices, such as RAM and DRAM chips, magnetic devices (ranging from magnetic tapes to disks to magneto-optic devices) and optical systems including optical disks (CD-ROM's) and volume optical memories such as holographic and two-photon devices. The reason for the continuing competition among these disparate technologies is that each brings its own strengths and weaknesses to the field and none fulfills every need. Among the performance attributes considered for storage technology are capacity, access time, throughput or transfer rate, reliability, removability, erasablility, storage lifetime, robustness, and, most importantly, cost. In the past few years a number of comprehensive reviews of these technologies have been published and we freely cite these here.[1-4]

2.1 Solid-State Memory

There are three essential levels of computing storage capabilities used in today's standard architectures. These are well described by Esener et. al. in their review.[2] The three levels consist of primary (or main), secondary and tertiary storage and describe increasing capacity and increasing access times. Primary memories connect directly with the central processing unit (CPU), are generally implemented in silicon and, due to limited proximal real estate, are limited in capacity (10 - 100 megabytes). They have fast access time (tens of nanoseconds). The capacity of DRAM has increased at a rate of about 60% per year.[3] The fastest RAM chips (static RAM) have improved in speed at about 40 percent per year, and DRAM, while improving is doing it at a slower rate. These rates are expected to continue over the next decade.

2.2 Magnetic and Optical Disks

Secondary storage, consisting of magnetic or optical drives, provides less expensive, higher capacity systems, but with much increased access times. The standard technology for secondary storage has been and continues to be magnetic disks with capacities ranging up to tens of gigabytes. Over the past decade the performance of this technology has continued to improve beyond expectations, with disk density doubling every three years.[3] This improvement has resulted in smaller formats and improved reliability culminating in the RAID (redundant arrays of inexpensive disks) systems which allow parallel use of multiple disks giving both redundancy and error corrections. Performance of magnetic disks is now at a stage where, in order to achieve substantial gains in improvement, cost becomes critical because the heads need to be ever nearer to the disks.

Competing with magnetic disks are optical disks such as CD-ROM's. For these systems, a focused diode laser reflects off data represented by minute pits embedded in the disk. These systems typically have slower access times than magnetic disks, primarily due to the mass of the moving head,[5] but this gap is closing.[3] Capacities are on the order of 600 megabytes per disk with access times on the order of tens of milliseconds. In spite of this slowness, their ease of portability, robustness, and convenience of use make them a very competitive medium for many applications. Magnetic drives do not have the required capacity in a single reliably removable disk.[3] WORM (write-once-read-many) optical disks are available with a total capacity of about 10 gigabytes for 14" disks Erasable systems using magneto-optic materials are also under development. These systems require more complicated heads to read and write the magneto-optic material that works by changing the polarization state of light. The Air Force's Rome Laboratory has sponsored development of useful systems of this type, including a jukebox capable of a terabyte of storage.[6] The jukebox or multidisk system allows greatly increased capacity at the expense of added complexity and access time to locate the appropriate disk. The fundamental limitation of optical disks is their slow access time, limited by the rotation speed of the disks and movements of the heads. Parallel access of optical disks is expected to increase the speed substantially; and blue diode lasers, currently under development, will allow higher densities.[7] This latter improvement occurs because the minimum resolvable size of an optical spot is proportional to the square of the wavelength.

2.3 DVD

Expected by the end of 1996 is the latest in optical disk technology, the so-called DVD's (digital versatile disks).[8] This new format will show a number of improvements over previous ones, in particular higher capacity. Compared to the current CD format allowing 0.68 gigabytes, the new DVD's will hold up to 17 gigabytes of information. This improvement is accomplished by a combination of several changes. The new disks will have two layers for data, either on two sides, or on one side, giving 9.5 or 8.4 gigabytes total storage, respectively. Some may have four layers, two on each side, giving the 17 gigabytes total capacity. Other changes accounting for this storage improvement include shorter wavelength lasers (630 nm compared to 760 nm), shorter pit lengths and a larger numerical aperture for the optical stylus. By 1998, read/write capable DVD drives are expected. Both DVD-R (write-once) and DVD-RAM (multiple write/read/erase) versions are expected, with the DVD-RAM using phase-change materials, rather than the magneto-optic ones used in current multiple-write disks. The playback drives for these phase change materials should use the same technology as for a standard ROM drive, thus simplifying the playback heads.

2.4 Tertiary Storage

Tertiary or archival storage is the final level. It usually consists of libraries of magnetic tapes with their concomitant very large capacities (terabytes) and very slow access times (up to minutes). These installations require large space for storage and may amount to the most expensive overall component due to the large numbers and storage space requirements. Arrays of optical disks (so-called jukeboxes) are becoming very popular for archival storage due to their reliability and compact size and convenience.

2.5 Hierarchy Gaps

Although all these technologies are continuing to show incremental improvements, there exist several gaps in the hierarchy. One of these gaps can be described as the I/O gap[3] where storage technology has improved at a rate slower than that of the microprocessor at the core of the computing system. In this sense, computing evolution has been held back by the speed and capacity of the memories. In addition, there are substantial gaps in both the access speeds and capacities between primary and secondary, and secondary and tertiary storage. These gaps are best illustrated by plotting transfer rate and capacities versus access time for available storage device types. This has been done by a number of authors [1,3,4] and we reproduce such a chart in Figure 1.

One limiting factor of these storage technologies is their simple planar format. This fundamentally limits the densities available. In optical systems the limits are basically caused by diffraction such that the smallest resolvable spot is on the order of the square of the optical wavelength. Hence shorter wavelength lasers are needed, but even this would only improve the capacity by at most a factor of three to four. Typically, to gain an entrance in the marketplace, new technologies need to provide at least an order of magnitude improvement over existing ones. This can come in the optical regime by moving to full volumetric storage, thereby utilizing the third dimension of the media. Such systems will allow for higher capacities, but also faster access times due to improved parallelism. By allowing an entire plane to be read in or out at a time, the data rates can be substantially increased.

There are a number of optical technologies under development that will do just this. Among the most promising are holographic storage and two-photon storage techniques. These two technologies which are described below, have many similarities but are fundamentally different in that the two-photon storage is a bit-mapped technique where the data are localized in the storage medium. Holographic storage, in contrast, is a distributed medium where all the data are stored throughout the medium. This has some advantage due to less sensitivity to localized damage, but any medium damage will reduce the signal for all the data. More developmental technologies are the coherent optical techniques such as photon echo and persistent spectral hole burning. Probably the farthest out in the development curve are so called molecular memories. In the next section we discuss these technologies in terms of their promise and problems.

2.6 Holographic Memory

Research in holographic memory systems has seen a great resurgence in the past few years, mainly due to improvements in materials, multiplexing techniques and auxiliary required technologies such as detector arrays.[9-16] Holographic recording preserves the interference pattern between two coherently mixed laser beams. One of these beams carries the data, spatially imprinted on it, and the other serves as the reference beam. By modifying the reference beam in a given way such as changing its travel direction (angular multiplexing) or phase distribution (phase multiplexing) multiple unique holograms are recorded in the same material volume. Each individual hologram can be viewed as storing a page of data; and by multiplexing the pages, the required storage capacity is increased. The data are read out by an appropriate readout beam that reconstructs the original angle or phase of the reference beam. Demonstrations of up to 10,000 complex images multiplexed in a small cubic centimeter size volume have shown successful storage and retrieval.[9]

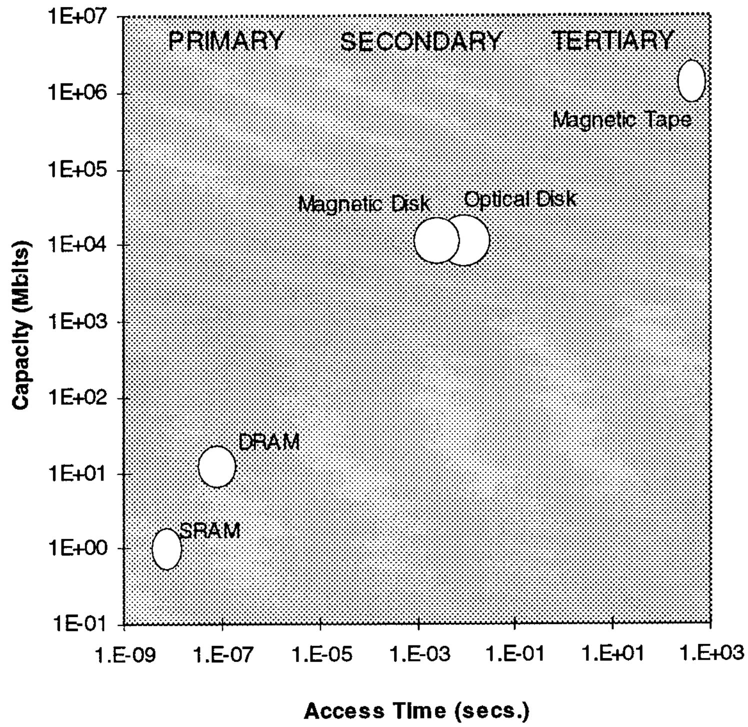

Figure. 1 Capacity vs. access time for available storage memory types

The recording of the interference patterns of holograms depends on appropriate recording materials that allow a suitable change in the refractive index. Materials ranging from photorefractive crystals such as $LiNbO_3$ and $BaTiO_3$ to photosensitive organic film such as is being marketed by Dupont, are being optimized.[10,11] Photorefractive materials have a complication in that there is erasure during subsequent exposure, be it during readout or additional multiplexed writing. Some materials can be "fixed" to allow the refractive index grating to be semipermanently stored, and multiplexed images can be individually timed to achieve maximum recording efficiency with minimum erasure. Another problem with photorefractive crystals is their cost for reasonable crystal sizes. The Dupont photopolymer film is inexpensive, easy to work with and non-erasable. For a read-only type of memory, it shows promise.[10,11]

The potential for high capacity, fast access memories with holograms comes from the parallelism provided by the storage of multiplexed images. Hong et. al. [12] present sample numbers based on image page sizes of 1 Mbit of data. By multiplexing 500,000 pages, a total data capacity of 500 Gbits is achieved and by reading out a 1 Mbit page of data at a time, in the 100 μs typical detector array response time, a total data transfer rate of 10 Gbits/s is achieved. The 500,000 pages can be achieved by multiplexing 10,000 holograms in a common volume and spatially multiplexing 50 of these in a layered stack.

A number of organizations are currently working on demonstration systems for holographic memories. Holoplex [15] has developed and delivered a commercial memory product that stores up to 1000 640 x 480 pixel images. The system is for fingerprint identification. Rockwell [13] has demonstrated a system using acousto-optic addressing. The intended use is for avionics applications allowing no moving parts due to vibration and shock environments. Researchers at Cal Tech [10,11] have demonstrated a 3-D disk using the Dupont photopolymer laminated onto a glass disk substrate. Finally, the Holographic Data Storage System (HDSS) [15] consortium is intending to produce an operational holographic data-storage system in the next five years. The stated goal is to develop write-once and rewritable holographic data-storage systems capable of storing as much as 1 Tb of data with an access rate of 1 Gbit/s.[16] The Photorefractive Information Storage Materials (PRISM) consortium is looking at problems in the material systems. HDSS has recently reported a precision optical test stand for systematic evaluation of materials and techniques used in holographic data storage.[14]

2.7 Two-Photon Optical Memory

Two-photon optical memory systems represent another volumetric optical memory technology with attractive attributes.[1,4,17] In these systems the memory material consists of a photochromic dye embedded in a polymer host that changes its molecular state upon illumination with the appropriate light. Writing to the material requires the simultaneous excitation by two photons from two separate light beams. Reading is accomplished by either illumination with one or two photons which causes the written molecule to fluoresce. The requirement of two simultaneous photons allows addressing individual volume elements in the medium by suitably directed optical beams. One beam can be configured to represent a bit, a vector or an entire plane of data such as impressed by an SLM. The second beam addresses the recording area by the location of its intersection with the data beam. The beams can intersect orthogonally or can counterpropagate. In the counterpropagating case, the address is selected by appropriate timing of the intersection. In this case, sufficiently short pulses are required to delineate the plane of memory. Pulses shorter than 50 fs are required for a recorded plane of 10 μm depth.

Two-photon memory materials and systems are being actively developed at Call/Recall, Inc.[17] Advantages of the technology include the inherent low cost, robustness and workability of the material. The polymer matrix host can be machined or molded to any desirable shape. The molecular change in the dye, caused by the intersecting light beams can change a number of properties of the medium such as its absorption properties, refractive index or electrical configuration. Call/Recall is investigating a number of dyes with appropriate characteristics. Among the desirable characteristics are low recording energy and high fluorescence efficiency. For dyes that undergo an absorption change, it is important to have good separation between the unwritten absorption band and the written band. Some of the materials studied are optically erasable, either in bulk by flooding the entire sample with a strong pulse of light, or by individual bits or planes by exposing only the desired region. Among the disadvantages with some early material systems were relatively short written lifetimes at room temperature. Cooling to 3° C extended the lifetime from about an hour to several months. Some newer media systems show longer room temperature lifetimes and erasability.[18]

This type of memory also has requirements on the lasers for writing and reading. The low power CW readout laser imposes fewer requirements. Besides the standard needs of low cost and compact size, good mode and wavefront quality at the appropriate wavelength are the essential requirements. Some appropriate low cost lasers are already commercially available. These include diode-pumped Nd:YAG "chip lasers." The recording lasers have more stringent requirements. These stem from the two-photon absorption process which requires high peak powers that are most efficiently generated by short pulsed (mode-locked) lasers. The pulse trains must illuminate the material simultaneously thus requiring synchronized picosecond or even femtosecond pulses. This is most easily accomplished by generating both pulses in the same laser and using nonlinear techniques such as second harmonic generation to obtain the appropriate wavelengths. High repetition rates allow fast recording times, but there is a tradeoff between high pulse powers and repetition rates. These three (pulse power, repetition rate and recording times) may need to be traded off in the ultimate system. In addition, to the previously mentioned requirements of good wavefront quality, pulse-to-pulse uniformity and lateral mode intensity uniformity are necessary.

Call/Recall reports on two recent demonstration systems,[18] one for automatic recording and one a portable ROM system. The recording system stored multiple images created from chrome-on glass masks. These masks were illuminated by an expanded and collimated beam at 1064 nm. The resulting images were then focused into a cube of the memory material. The image was stored in the cube by simultaneous orthogonal illumination with a sheet of 532 nm light. The memory cube, focusing lens and the chrome masks were mounted on motor driven linear stages to allow automatic stepping through the various images, to position the cube relative to the addressing beam and to focus at the appropriate memory plane. The portable demonstration ROM system was designed to read the images in the cube written by the automatic recording system. This system was designed to be simple, lightweight, compact, and use easily available commercial parts. It consisted of a compact He-Ne laser used at 543 nm. The laser beam was sent through an anamorphic telescope to create a thin sheet of light to address the appropriate image plane in the memory cube. The resulting fluorescence was collected by a CCD camera and displayed on a video monitor. The video cube is moved by a stepper controlled stage to allow the addressing beam to illuminate different planes. As the cube is moved, the camera focus shifts due to the varying optical path length through the cube. This focus shift is compensated for by moving the camera at the appropriate rate. This is accomplished by the use of a dual speed stage to move both the cube and camera. This system, minus the control electronics, power supplies and video monitor fits in a shoebox sized box and has been transported to various Air Force sites for onsite demonstrations.

Due to the volume nature of two-photon memory materials, the theoretical capacities are projected to be very high, on the order of terabits/cm^3. Using the parallelism inherent in working with full images, this technology is also expected to be very fast, from Ghz to 100's of Ghz. The access times are only limited by the technology required to read out the detector array since reading and writing times are so fast. For counterpropagating beams, the access time could be as fast as a microsecond,[1] the time required for an optical pulse delay device. In the orthogonal architecture, the access time is determined by the device used to focus on the desired image plane. For a dynamic focusing lens, this could be around a millisecond but faster accessing technologies would speed this up. There is a tradeoff between data transfer rate and capacity, however. The fastest transfer rates rely on the parallelism that arises with reading full vectors or images at a time. However, primarily due to the limitations of diffraction, as one goes from single pixel images to large two dimensional arrays, the volume density decreases. This is illustrated in a Table I taken from Reference 17 showing the maximum volumetric density for various data formats in orthogonal memory systems operating at 1 μm wavelength. In this table the addressing beam thickness (T) is determined by Gaussian beam propagation. A similar trend occurs in counter-propagating addressing schemes.

Data Format	Pixel Size $P_X \times P_Y$ μm x μm	Array Size $N_X \times N_Y$	Addressing Beam Width $W = P_X N_X$ μm	Addressing Beam Length $L = P_Y N_Y$ μm	Addressing Beam Thickness μm	Maximum Volume Density (bits/cm^3)
Bit	1×1	1 × 1	1	1	1	1×10^{12}
Vector	5 × 5	256 × 1	1280	5	2	20×10^9
Image	5 × 5	1 × 256	5	1280	33	1.2×10^9
	5 × 5	16×16	80	80	8.2	4.9×10^9
	5×5	128 × 128	640	640	23	1.7×10^9
	10×10	1024 × 1024	10240	10240	93	0.1×10^9

Table I. Storage capacity as a function of data format (from Reference 17)

Holographic and two-photon memories reflect a number of similarities. They both require reading and writing lasers, and they require similar auxiliary technologies for inputting and outputting the data. For imprinting the data onto the writing laser beam, spatial light modulators (SLM's) are used and detector arrays such as CCD's are used by both memory types for converting the light data to electronic form. Both of these technologies are rapidly improving due to consumer market demand in other areas. For CCD's and detectors, the market is being driven by the multimedia consumer market and devices with suitable cost and performance are available. Electronic imaging applications are driving detector array development and the flat panel display market is forcing improvement in performance and cost of liquid crystal display panels that can be used as the necessary SLM's. The maturation of these components has made feasible the recent system demonstrations of holographic and two-photon memories.

2.8 Persistent spectral holeburning

Persistent spectral holeburning allows information to be stored in a material by changing the characteristics of a broad absorption band.[19] Data is encoded as a wavelength-dependent modulation of the absorption band and recalled by appropriate illumination of the band with laser light. For successful storage and recall, several conditions are required. The absorption linewidth of the individual absorbers, the homogeneous width, must be very narrow. The inhomogeneous absorption linewidth must be much broader. This linewidth results from random frequency shifts of the individual absorbers, resonances in local crystal fields and strains in the material. Materials fulfilling these two conditions, known as inhomogeneously broadened materials, come in a number of forms, one of which is produced by doping absorber ions into a crystalline or glass host.

Upon illumination by single-frequency narrow-band laser light, absorbers in resonance with the excitation transition to an excited electronic state. In most materials, when the excitation is removed, the excited absorbers decay back to their ground state. However, in some materials there exists an alternate state into which the some of the absorbers may decay. If this alternative state has a different energy than the original ground state, and is sufficiently long lived, then these absorbers fall out of in resonance with the original excitation. In some materials, decay into this reservoir state may even be assisted by an additional gating radiation field at a different wavelength than the excitation wavelength. This process is termed "gated storage" and it has the advantage that the reading process is nondestructive and the writing process is typically more permanent.[20]

Reading of the stored data is achieved by frequency scanning across the absorption band with a laser. A spectral "hole" is created at the wavelengths where absorbers have relaxed into reservoir states causing decreased absorption. The number of these spectral holes allowable in a single physical location is roughly given by the ratio of the inhomogeneous linewidth to the homogeneous linewidth. This number can be as high as 10^7 in some materials at liquid helium temperatures.[21] In practical materials this ratio may be only 10^3, but this still represents an enormous increase in information storage density compared to the storage densities possible with conventional two-dimensional spatial storage techniques. Frequency tuning the laser can give gigabyte storage and access times of submicroseconds with the access times determined by how fast the laser tunes. Electro-optic (or acousto-optic) scanning could give of up to terabytes of data with increased access time (tens of microseconds). Transfer rates would be as high as tens of Mhz per page.

2.9 Coherent Transient Memory

Coherent transient memories rely on these same selective absorption properties of inhomogeneously broadened materials. They work using the output signal emitted from an inhomogeneously broadened two-level absorber after excitation by three temporally encoded light pulses. The first two waveforms, temporally separated and angled with respect to each other, form the reference and data pulses. As long as these waveforms satisfy three conditions, the medium will respond to their combined power spectrum. These conditions require the waveforms to be within the inhomogeneous bandwidth of the absorbing transition, be shorter than the transition's homogeneous lifetime, and to not saturate the two-level transition. The resulting power spectrum contains an interference term proportional to the product of the Fourier transforms of the waveforms. This interference is stored in the spectral population distribution of ground state absorbers. It forms a spectral hologram analogous to the spatial hologram produced by the interference of two spatially modulated light beams with angular separation. These interference patterns can be stored permanently, enabling long term memory or continuous data processing. The resultant grating spectrally filters the Fourier components of subsequent optical inputs and can, under appropriate conditions, give an output mimicking the original data pulse, hence the common term "photon echo." The requirements for the output pulse to mimic the input pulse include that the first and third pulses be either temporally brief with respect to the modulation of the data pulses, or identically frequency chirped pulses with chirp bandwidth greater than the data bandwidth, or identical pseudo-random broadband pulses. A coherent transient memory system can store frequency, phase or amplitude modulated encoded data but the bandwidth is ultimately limited by the inhomogeneous bandwidth of the absorbing transition.

These types of memory are projected to have capacities exceeding hundreds of terabits per cubic centimeter. Data bandwidths ranging from hundreds of megabits to terabits per second are possible. As with other memory types there is a tradeoff between capacity and bandwidth. A major stumbling block in the inhomogeneously broadened memory has been materials development. A new concept in holeburning memory, swept carrier,[22] is a hybrid of the time-domain and frequency-domain approaches that adapts to maximize a particular material's attributes thus greatly increasing the number of potential practical materials. Even so, the requirement of a large inhomogeneous to homogeneous bandwidth requires cryogenic temperatures (typically less than 20 K). Practical systems will only be built once the temperature limitations are overcome or cryogenic operations become more widespread and usable. This trend may be on the immediate horizon.[23]

2.10 Molecular Storage

The concept of molecular computing and storage is really in its infancy and as such will not be discussed much here other than to mention it is currently being looked at by researchers. The concept relies on the observation that molecular reactions occur very fast and in parallel. The field might be considered to have originated with a talk by R. Feynman [24] on the possibility of building "sub-microscopic" computers. but it gained renewed interest in 1995 when L. Adelman built a "computer" in a test tube of DNA.[25] In this "computer" the chemical reactions that a particular synthesized DNA sequence underwent produced a molecule that when decoded, answered a specific well-posed problem. Storage is viewed as the simplest task for a DNA computer. Data would be encoded into DNA sequences and the DNA could be stored. To retrieve data a DNA strand designed so that its sequence attaches to the key word wherever it appears in the stored DNA would need to be synthesized. This type of memory would be able to hold thousands of terabytes in a test tube, (1 bit per cubic nanometer or 10^{21} bits/cm^3 according to Adelman); but its access time would be very slow (minutes to hours). Over the time frames of interest to this study, this technology is not expected to be sufficiently developed to be of use.

Using the projected improvement numbers for the competing technologies we have plotted the projected performance in 2005 in Figure 2. In comparison with Figure 1, we find the following trends. Solid state memory will probably still be the fastest, and although its densities will have improved substantially, they will not approach the total capacities available on disks. Magnetic and optical disk performances will be quite similar. Magnetic tape stays the same. The new entries for optical memories, both volume bit-wise or holographic and coherent transient types fill a new niche - that for faster access, with much higher capacities.

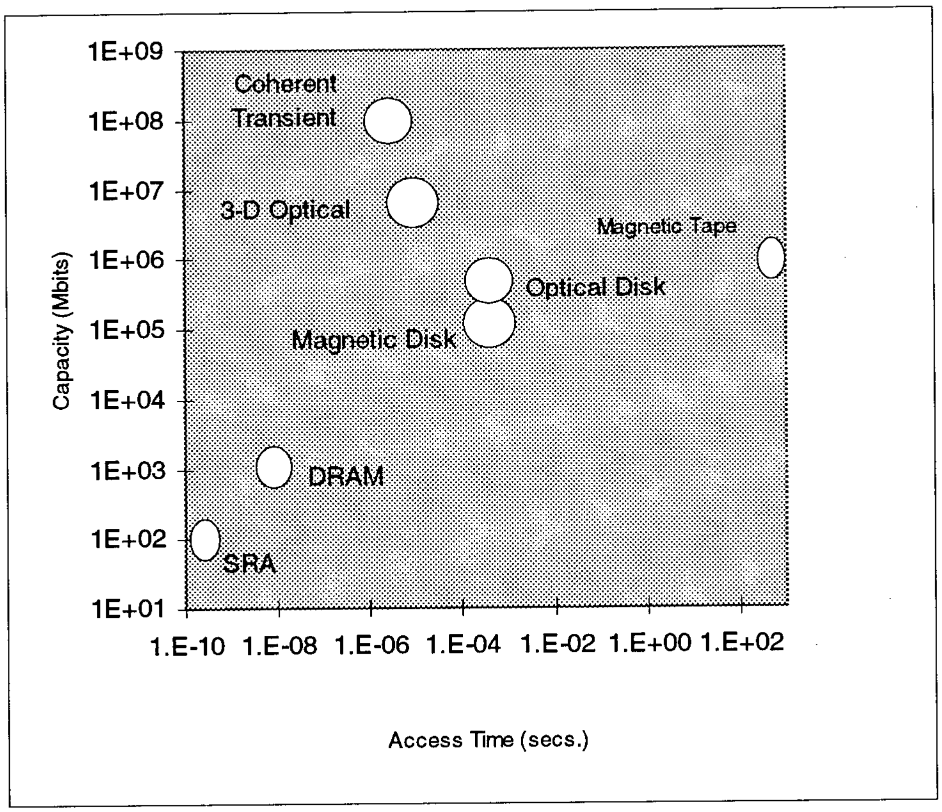

Figure 2 Projections for memory capacity vs. access time in 2005.

2.11 System Performance

One fundamental system performance parameter has not yet been discussed. This is reliability or data integrity. Typically the bit error rate (BER) is used to describe this property relative to a particular medium. Optical media typically have larger raw (uncorrected) BER's than magnetic, due to their higher density.[5] A given size defect on an optical disk obscures more data than on a lower density magnetic disk. However, a more useful parameter is really a corrected BER after error correcting coding has been applied. BER's are typically measured by writing pseudo-random data to a medium and counting the incorrectly recovered bits. However, such a statistical test does not allow prediction of system performance under different operating conditions. To enable such predictions, a complete channel model for the entire system, including the medium, system architecture, noise mechanisms, error correction and full I/O channel is required. Such models require substantial experimental work for development and validation, and very few systems currently have them available. For true extrapolations of system performance under varied operating conditions, appropriate channel models need to developed. This would allow optimization of system performance and development of tailored correction codes for the specific system. Among new codes being formulated for optimum performance are those specifically intended for 2-D data.[26]

3.0 Application Programs

The programs reviewed for this study are all active contracts or internal programs within the Boeing Company. They were selected as being likely to have significant needs for high capacity fast access storage over the next decade. They were chosen to cover the different types of operating environments including both airborne and ground-based and to cover both military and commercial uses, although military uses were of prime interest. We attempted to concentrate on Air Force programs, but also considered both Army and Navy applications. Due to limited resources, we have not included any space-based programs, although some promising ones that could be considered are listed at the end of this report. For each of the programs detailed below, we have either personally or via the telephone interviewed personnel working with and intimately connected with the particular program. In the course of the interview, we have presented information about the Call/Recall technology under development to educate potential future users. While some showed a degree of interest in how the two-photon memory actually worked, most of their interest lay in the performance expectations: how much capacity, how fast, when it would be available and of primary concern, how much it would cost. Most of the military programs are currently being urged (if not legally contracted) to use COTS (commercial off the shelf systems) to help in reducing their system costs both for components costs and reduction in oversight required for custom orders and one-of-a-kind parts. At the same time, they are often expected to follow the requirements set down in the MilSpec requirements sheets, or their current replacement. For example, MIL HDBK 5400 gives the requirements for electronic equipment on piloted (and presumably also unpiloted) aircraft.

Some programs have expressed skepticism and concern about the technology and others have shown great excitement to learn about it. Some even wanted to know if a "Beta" version was available now for testing. Most of the skepticism expressed came in the area of ruggedness and packaging of the technology. Some flight-based programs had looked into optical (disk) storage in the past in defining their requirements and dismissed it mainly due to concern over ability of the moving heads to perform in high acceleration environments. Other skepticism was voiced by people working on fighter avionics about how to provide adequate cooling of the systems.

We have attempted to obtain for each program the following information. First we obtained a description of the functional mission of the program - that is what they are trying to do and what the technology is expected to provide. Next, we looked at, what the operating environment is and if there any special environmental concerns. An example of a special concern is that for some military planes, the equipment must be nuclear hardened. Some others may be deployed on aircraft carriers, a particularly harsh environment. The next critical piece of information is what equipment is currently used to perform the mission. What are expectations for growth requirements over the next decade and what do they expect to use to obtain this, are the final questions. In some instances it proved very difficult to coax program personnel to come up with numbers for future storage requirements. In these cases we have tried to make best estimates based on similarity to other programs, or information obtained from people working on similar technologies in internal research and development efforts. As mentioned in the introduction, we also obtained useful information from the Boeing division looking at concepts for future business.

This section briefly summarizes the programs presented in more detail below. They are nominally presented in order of increasing environmental requirements. The first program applications are for ground-based programs. These have less onerous environmental problems and are more suitable for near-term field tests. One area of large interest and growing importance is Computer Based Training (CBT). This is important in both the commercial and military arenas. In these scenarios, lessons are stored on disks and served from file servers to a potentially large number of users. Boeing has a large training facility devoted to pilot training and aircraft maintenance training. In addition, Boeing has an Air Force contract to provide flight, support and maintenance training for the F-22 fighter. This F-22 training system will rely heavily on CBT. The next application is of interest to Boeing in the commercial arena, but there are definitely military analogs. This is the field of Air Traffic Management. In this application, there is interest in recording all the information available to the air traffic controllers from their computer monitors throughout the length of their shift. This information is of prime importance in accident investigations. The final ground-based program we explore is the DEMPC (Data Exploitation Mission Planning and Communications) program, to provide mission planning information for the Predator UAV vehicle. Mission planning is an area that requires the synthesis of a great deal of information, much of it imagery. Several other programs we studied also deal with mission planning. This is also the first of several programs studied that has or anticipates a need for large amounts of map data, primarily from the DMA (Defense Mapping Agency).

The first airborne system we examine is a commercial one, but again, it has military counterparts. This is the Boeing flight test facility that records information, primarily avionics data, during flight tests of new aircraft prior to FAA certification. In addition, this organization sometimes has requests from customer airlines to monitor delivered aircraft performance. The VCX-SAMCOMS (Special Air Mission Communications Systems) program is looking at military derivatives of commercial airplanes, such as executive jets for high ranking government personnel. Requirements include full multimedia work stations in flight, but these systems are not flight critical or for flight control, but rather for use in the passenger cabin. In that sense, they have much less stringent operating requirements. The next program is for the Army, but is sponsored jointly by other agencies. This is the ATIMS (Airborne Tactical Information Management System) which has been described as "the virtual reality helmet". In this program, pilots are presented with information, viewed through a heads up display (HUD) that allows them to perform mission planning. They can practice the mission beforehand and also record the information received during the flight. The B-1B, JSF (Joint Strike Fighter) and F-22 are three Air Force planes or proposed planes with varying missions requirements and schedules for upgrades. The F-22 and JSF which are in development stage have some similarities in their avionics and thus have similar storage requirements, although their missions and operating environments are substantially different. The B-1B Program is upgrading the current systems in the bomber to fit it into new missions in the "post Cold War" era. Next, we consider the UAV (Unmanned autonomous vehicle) programs under development for the Air Force. Although some of these have actually been used in Desert Storm, this is in general an area of rapid development with evolving requirements. Finally, we consider some requirements for Integrated Battlespace scenarios and list some programs that have potentially large storage requirements, but which we have not examined in detail.

3.1 Computer Based Training

With the advent of desktop PC's, multimedia workstations and widespread network servers, Computer Based Training (CBT) has greatly expanded. In this application, prerecorded lessons are served to students interactively from a central server system. This particular application has many commercial and military applications and we present here two examples, one for commercial systems and one military program with CBT requirements. The advantages offered by CBT include reduced costs due to reduction of paper-based copies and reduction of ongoing instructor time. In addition combination of multimedia and textbook lessons maintain student interest and increase the long term memory of the lessons. One of the great advantages of these programs is their benign office environment, thus making them useful potential testbeds for new technology.

For a long time the Boeing company has provided the service of training flight crew and maintenance crew on individual airplane models ordered by customer airlines. This is one area where personnel really are driven by the best available consumer marketplace technology. Just in the past few years, with the arrival of inexpensive, consumer, multimedia technology this area has expanded considerably. A major changeover occurred with lessons created for the new 777 model airplane. Here personnel made use of the latest technology and lessons are offered on Pentium-based machines using CD-ROM's. Pre-777 lessons (on older model airplanes) are offered on 386-based machines using video disk technology. Lessons are now offered with full motion MPEG video clips as well as audio and large amounts of bit-mapped imagery. These are all, particularly the video and imagery, very storage hungry technologies. For the lesson scenario, a WORM disk would be appropriate since the lessons are updated infrequently, maybe several times a year. Thus if the memory were inexpensive enough, the old disks would merely be discarded and replaced with updates. In addition, ROM disks would be used for archival storage. Also, writeable disks in the authoring environment would be required for people creating the lessons. In such scenarios, the disk capacity requirements are expected to be a factor of 10 larger than the delivered lesson disks. At this time, the servers used to provide the lessons consist of 2 SPARC 1000 systems with 12 gigabytes on each server. Data storage is done with external disk packs that use RAID arrays, storing from 18 to 48 gigabytes. Typically this information is served out to 200 workstations and this number is expected to double in the next few years. As lesson sizes increase in the future, this capacity will also need to increase. Capacities up to hundreds of gigabytes and even up to terabytes are reasonable. In addition to a WORM disk, cache memory is likely to be needed in the server application to preload lessons in high demand. The capacity required is very dependent on the overall server architecture but it likely to be at least a gigabyte.

Currently existing lessons provided for 777 maintenance and flight training consist of a series of about 100 lessons lasting about 20 minutes each. The existing lessons contain raster data, digital audio, animations and text. They require about 3-4 gigabytes and use transfer rates of 300-500 KBps. Planned lessons for the 767/757 models for next year (1997) have estimated requirements of up to 14 gigabytes with transfer rates of 400-500 KBps. These include the current type of data plus digital video and database tables. Another model of the 747 airplane will be coming on line in about 4 years (2000) and anticipated required transfer rates are 1 MBps with similar capacities to the 767 models. Over the next ten years, new airplanes are anticipated to require up to 20 gigabytes and transfer rates up to 20 MBps. These will include 3-D animations and real geometry ("virtual reality walkthroughs"). Added to the requirements listed above, are the on-line maintenance documents. Currently these are available in a portable maintenance aid (PMA) for service technicians of customer airlines. Each airplane model has about one gigabyte of documents stored. For a complete field service office, to handle all models for all customers, this on-line documentation could be up to 200-300 gigabytes. This number could be added to the lesson requirements if this is implemented. These numbers are all for delivered products. For production of them, the requirements could be a factor of ten higher; and for archival storage, the number of lessons for each model needs to be multiplied by the number of customer airlines, say 10 to 20. For all of these applications, the environmental constraints are quite benign, such as typical office environments, so standard consumer product requirements should hold.

The other CBT application is the military one of training for F-22. F-22 is the Air Force's new generation Advanced Technology Fighter capable of supersonic flight and high-g maneuvering with advanced offensive and defensive avionics. It is currently in the E&MD (Engineering and Manufacturing Development) stage. Among the Boeing contract requirements is to train the personnel that will fly, support and maintain the F-22. The training system is scheduled to be operational in 2002 and its expected life is 30 years. Most of the parts of the training system will be demonstrated before 2002, and where appropriate, will use COTS hardware and software.

The mass memory requirements are being driven by the CBT portion of the training system. The CBT will support animation, graphics, digital photography (i.e., JPEG), digital sound, digital video with sound (i.e., MPEG-1, Editable-MPEG-1, and perhaps MPEG-2). The projected data storage requirement for the year 2000 is 400 gigabytes (i.e., about 400 lessons each about 1 gigabyte). This might grow as more video is included in the lessons and various updates to the hardware and training are incorporated. The location that creates CBT content will require at least 1 Tbyte of on line mass storage. Archival storage using magnetic tape, optical disk, or magneto-optical disk is being discussed. Read and writeable DVD is also under consideration.

The CBT data base will probably be replicated and stored at some number of geographically separated locations. It is expected that the data will be retrieved frequently but infrequently updated. The most bandwidth intensive mass storage application will be video-on-demand. In this application users can request any portion of a number of video clips at any time. Somewhere between a few dozen to over 100 workstations at a single location could be attached to a single server. (For example 200 workstations each requiring, say, 15 Mbps would place a 3 Gbps demand on the mass storage system). Because the peak bandwidth requirement can be a significant cost driver, video will be used sparingly throughout the CBT lessons; and it is not expected that all of the workstations will simultaneously require high quality video-on-demand. Currently the F-22 training program is expecting that one or more RAID arrays (using magnetic disks) will satisfy their projected F-22 training systems requirements for storage capacity, throughput and reliability. However, one of the group's tasks is to coordinate with industry and academia to stay abreast of emerging technology that would help this program. As such they are very interested in significant developments in optical memories.

In addition, although we could not obtain any specific requirements, the AWAC's organization is beginning to look into computer based training for their customers. The requirements should be similar to F-22 except that there will be many more lessons. For the AWAC's application, they are envisioning making all the technical manuals electronically available and each lesson needs to be available in all the languages of countries currently using AWAC's. This includes France, Saudi Arabia, Japan and perhaps Korea. They hope to eventually provide the lessons over something like the World Wide Web and include full digital video, audio and 3-D animation. Such requirements could easily raise the disk capacity required to terabytes.

3.2 Air Traffic Management

Another area with both commercial and military interest is in the field of Air Traffic Management (ATM). Very shortly, the Air Force will select the industry team to be awarded the STARS (Standard Terminal Automation Replacement System) contract, a joint FAA/DoD program to replace existing FAA and DOD TRACONs (Terminal Radar Approach Control Systems). This will be a complete digital system for tracking all aircraft with a defined airspace to be installed at existing FAA and DoD control centers as well as training facilities. As this program is currently in proposal selection phase, and Boeing is on one of the industry teams that have submitted a proposal, program personnel were reluctant to discuss details of this particular program. However, the general question of ATM was discussed. There are currently a number of other countries looking to upgrade their ATM systems including a Canadian upgrade being done by Hughes in the next 2-4 years, and various Asian countries.

One of the primary desired facilities now for ATM is an inexpensive high capacity recording system that can be installed at each controller's workstation to record everything that goes to that controller's screen. The prime use of such a system is for accident investigations. Currently in the Canadian ATM system, a feed off the monitor cable is used to record what goes to the screen. Because of storage limitations, not everything can be recorded, so they are limited to recording all the X-Windows commands that go to the screen. The desire is to have enough capacity to record an entire 8 hour shift so the controller could report for his or her shift, plug in the recording device and remove and take it along when the shift is over. With the current terminal sizes and refresh rates (2000×2000 pixels operating at 60 Hz) this could amount to recording up to 600 gigabytes during a shift, assuming no compression is used. This would be a good application for a WORM system using 3-D optical memory. Once the shift is recorded, the data could be preserved for a certain length of time, and then either destroyed or erased and reused, depending on the relative unit cost and ease of erasability. The environment for this use would again be a standard office type environment with corresponding environmental specifications.

Another more speculative ATM-related application for mass storage is also related to accident investigations. At the current time, the ground stations providing information to the cockpits are not required to be certified for flight critical components. The cockpit has been separated from the information that comes in from the ground. There has been limited display space in the cockpit as well as limited communication bandwidth. However, a current interest lies in giving flight crew more information to allow them more autonomy in determining their flight path. This vision includes using phased array antennas to provide a high bandwidth data link to the ground to bring large amounts of situational awareness information to the cockpit. This could include map and terrain data, information on all other aircraft in the area and weather information. As in some current military cockpits, the flight crew will not be able to monitor all the available information, but will need to have a lot of it stored and automatically analyzed to provide only the most critical information to the crew. In such a scenario, the ground station (where the information originates) and the cockpit become more tightly coupled, and some believe that the whole system (ground and cockpit) will need to undergo joint certification. In such a case, there would be a requirement for recording all the information transmitted for accident analysis. Such a system could easily require terabytes of capacity over transcontinental or transoceanic trips.

3.3 Commercial Flight Test

The Flight Test organization within the commercial part of the Boeing Company is responsible for testing new aircraft to pass FAA certification requirements. They also sometimes have tests required by specific airline customers. They have a need to record much information during the tests. Similar requirements are typical for military aircraft. Currently the most advanced data recording system used during flight tests, that used for the 777 certification, is a set of AMPEX DXRSi tape recorders. These recorders are capable of recording up to 65 Mbps on cassette tapes holding up to 48 gigabytes of data and a typical flight requires 2-3 tapes, meaning between 100 and 120 gigabytes of data. Such tape drives are expected to be installed on all airline models in the future. The bulk of the information stored is from the avionics buses. On the 777 airplane this consists of up to 50,000 parameters including 4000 analog signals and traffic on both the ARINC 429 and 629 data buses. There are some newer tape drives available with bandwidths up to 75 or 100 Mbps, but the current commercial system requirements are not bandwidth limited and not expected to become so in the foreseeable future. With all systems being recorded on the 777, the 65 Mbps was sufficient. Some military systems, however, can have greater than 200 Mbps bandwidth requirements, and some have had to resort to RAID technology to allow for this. The growth in commercial systems is expected to come in required storage capacity. Over the next 10 years, aircraft are expected to require more data buses with more information on each bus. Required storage capacities are expected to double or triple, hence requiring storage of up to 300-400 gigabytes.

Typically this information is recorded during the flight and required for multiple playbacks starting immediately after landing. The current tape recorder systems are described by users as being "an electromechanical nightmare and always in the shop for repair". Hence something solid-state, and more reliable is desirable. For this application, a WORM system capable of recording a terabyte would be ideal.

Another application of the flight test organization is for field service. Typically customers are interested in monitoring performance of specific instruments on an airplane. For example, one customer wants to monitor how fast the tires wear. To do this, a recording instrument is set up to monitor whenever the airplane is on the ground. Such monitoring can go on for months. The current system is limited to storing 5 gigabytes and needs to be changed once a week. A medium capable of more storage and requiring less frequent changing is desirable. For this requirement, a WORM system capable of storing 100 gigabytes would be desirable. The bandwidths required are minimal and the data format is simply streams of bits.

Environmental requirements for these systems are fairly benign. They reside in the cabin for flight test airplanes and in the equipment bay under the cockpit for field service applications. Temperature requirements are from 10°C to 55°C. Vibration is 2.6 G_{RMS} out to about 2 kHz. The system must operate under shock conditions of up to 6 G, survive up to 10 G and not fall apart to 15 G.

3.4 VCX- SAMCOMS

This is a range of programs in which the Air Force is looking at military uses for commercial widebody jets. One is the C32A program to replace Air Force 2, a plane for transporting high level government officials. The requirements for this system are relatively low, and as such is discussed in the Appendix. However, growth from these minimal requirements comes under a more demanding series of programs under the SAMCOMs umbrella. These planes are intended to have a full "office in the sky" to allow for full multimedia communications and full motion video information to the users. The time frame for this implementation is somewhat fuzzy, but expected to be over the next 5 to 10 years. Specific requirements are not yet set, but those mentioned here are projections. The requirements are similar to those reported for CBT. The main requirement for storage is for video servers.

Most of the current requirements being looked at are for the communications systems architectures, both LAN (local area networks) within the jets and WAN (wide area networks) for off-board communications. The video application is a most demanding one and will be required to handle the three standard video data rates. These range from 128 kilobits per second for standard ISDN lines used for video-teleconferencing to 1.5 megabits per second for the MPEG I standard used for full motion video to 4-6 megabits per second for MPEG II, another full motion video standard. Among the services expected are command radios, flight deck audio, a number of radio services, passenger entertainment and briefing systems including video conference and entertainment and multimedia, office equipment such as copiers, shredders, printers and laptop computers with large user storage, and various phone services requiring modems and FAX services. The implementation of these services is expected to require multimedia file servers on the airplane which will have considerable storage requirements; and the need for video-on-demand for up to several hundred passengers will require a very fast access random memory. Currently the prime technology competitors for this application are RAID 5 magnetic disk systems, but users are also waiting to see what will be available in the DVD marketplace. These are expected to store up to 25 times current CD-ROM's using MPEG II. One such unit currently being used is the Network Connection, Inc's. Cheetah Enterprise Server being used on project Speckled Trout.[27] Speckled Trout is an Air Force testbed (a Boeing C-135C transport) for communications and advanced avionics. The Cheetah server can handle up to 20 concurrent MPEG video streams accommodating up to 16 hours of video content and is expandable to 48 hours using RAID technology.[27] One of the prime enticements for RAID systems is their redundancy which gives fault tolerance. In the commercial airplane environment that drives Boeing, this is generally a primary concern and as such it permeates to most programs. However, the limit of 20 concurrent streams is set by the bandwidth of the magnetic disk systems.[28] Higher bandwidths of either solid state (more expensive) or optical memories are needed to increase this limit. This is another area where users expect the commercial marketplace to drive and define what they will choose from. The capacities expected are up to the terabyte range allowing for a large selection of multihour video presentations. It is expected that this would be divided between fast, short term cache memory (up to 10 gigabytes) and slower tertiary memory. Since these are essentially passenger jets, the environment is the same as listed in the flight test section.

3.5 B-1B

The U.S. Air Force's B-1B is a strategic multi-role bomber designed for all-weather, world-wide operations from any U.S. airfield or base on the globe. The operational concept requires a high degree of self-sufficiency to make the B-1B capable of operating under extreme temperatures, humidity, rain, snow, wind, sand, dust or pressure. Boeing is currently working on a series of upgrade programs for the B-1B avionics. These programs are termed "Blocks" and range from the current Block E out through Block G. The levels of requirements and degree of certainty for these requirements varies with the Block. Among the functionalities required are real-time information in the cockpit, map-aided terrain following, on-board mission planning plus guidance, controls and weapon delivery.

Block E involves avionics software and computer hardware upgrades. The upgrade is required because of limited throughput, memory and growth capacity on the current unit. The current system consists of a set of 4 IBM computers interfacing with a box of core memories with 1.2 megabytes of storage on tape cartridges. Part of the upgrade involves replacing the tape units with solid state cartridges from Fairchild. This component is currently used on F-15's and consists of 4-8 megabyte boxes. The Block E upgrade will require growth up to 400 megabytes. Hard requirements for Block E are currently being set. The E&MD stage of this program begins in 1997 with product deliveries out from 2000 to 2006 and deployment beginning in 2003. The requirements in this Block seem fairly modest, but even so they could have a need for more advanced optical storage. This program is currently being criticized by Congress for not performing upgrades quickly enough. Removablility (for security purposes) is important for their applications, and something with a much lower media cost is desirable. The cost of a single Fairchild storage unit is around $30,000 due to all the chips for the solid state memory. Program personnel are currently formulating a concept called "Block Now" that would allow rapid prototyping of hardware instead of waiting for the 2003 deployment date. This hardware would not need to be fully flight qualified, but would allow demonstration of functionality.

The operating environment for B-1B avionics is fairly severe, but overall the same as defined in the standard MIL HDBK 5400 document. One additional requirement is that all instruments must be nuclear hardened. This is not as difficult as it might first appear since equipment need only be packaged in a nuclear hardened box. The vibration environment is severe, much worse than on a commercial aircraft. The vibration environment differs whether the weapon bay doors are opened or closed. With the doors closed, the specification is 5.2 G_{RMS} over 20 to 2000 Hz, and for doors open, 6.2 G over the same frequency range. The temperature range is from -65°F to +160°F while operating, and -80°F to 200°F while not operating. The shock environment includes exposure to a 20 G peak terminal saw-tooth shock pulse of 11 ms duration. It must withstand 100% humidity including condensation, and dust concentrations up to 0.5 gm/ft^3, exposure in a salt-sea atmosphere, and fungus growth as in tropical climates. It must withstand explosive decompression and withstand EMP exposure. The space, power and cooling constraints are less of a concern on bombers than on fighters.

There exists a precedent for optical components on the B-1B. According to information available on their corporate world wide web site (URL: http://www.nml.org/industry/mountainoptech/companybackground.html), Mountain Optech's rugged SEL-2 write-once optical disk drives passed all aspects of the B-1B strategic bomber functional qualification tests. Environmental stress parameters emulated the severe shock and vibration environments of the ground-hugging aircraft with bomb bay doors open. The Mountain Optech SE-1000-M/F is used by the instrumentation system, to record a multitude of 1553, radar, and high speed digital data on the B-1B.

Block G needs for the B-1B are more demanding. These include upgrades to map-aided terrain following, in-flight mission planning, automatic weapon retargeting and Link-16 real-time data updates. Link-16 is the new NATO-wide data link standard. Some directives have been issued that state that at least some subset of Link-16 must be on all DoD planes by 2002. One function of Link-16 on the B-1B is to record imagery data for the length of the mission. At the 1.5 Mbps data rates and over the up to 35 hour mission, this can be well over 200 gigabytes. On-the-fly mission planning requirements allow retargeting of weapons based on satellite imagery which is used to send the correct image to the weapon. The time frame here can range from minutes to hours, This could easily require terabytes of memory. The autoretargeting function however needs quick response. If a weapon jams upon firing, all the target image information needs to be immediately sent to another weapon. Estimates are that millisecond access times will suffice for this, the most time-critical function.

The upgrades for increased functional capability listed above are currently being studied for the B-1B. Each of these imposes multi-gigabyte storage requirements on the avionics system. The sum could easily exceed a terabyte. On-board storage capacity will influence the effectiveness of the B-1B weapon system in terms of probability of survival and probability of kill. The quantification of effectiveness sensitivity to storage capacity is currently underway. B-1B personnel were very enthusiastic about employing 3-D optical storage technology. They cite the need to not move terabytes around the aircraft, but rather have the storage available where needed, particularly at the offensive and defensive system operator stations. They are enthusiastic about the capacity, and low cost of the two-photon media and its inherent ruggedness and survivability. In particular its apparent insensitivity to EMP (electromagnetic pulses), as compared to solid state memories, is considered by them as key advantage.

3.6 ATIMS

The mission planning function of the B-1B, mentioned as one of the upgrade functions above, is discussed more in this section. The mission planning function for the B-1B as well as other platforms, including the F-18 and V-22, is a main function of ATIMS (Airborne Tactical Information Management System). This is a program for the United States Navy Program Executive Office for Tactical Aircraft Programs, PEO(T), under the Space and Naval Warfare System Command (SPAWAR-32) Real-Time Support for Joint Power Projection Advanced Technology Demonstration (ATD) program. The work is being performed as a cooperative effort with the Air Force Avionics Directorate, Wright Laboratory (WL/AART) as a demonstration task under the Real-Time Targeting Concept Development (RTT) program. Among the supporting contractors are GDE Systems doing the system integration and Boeing Defense & Space Group doing the flight simulator and demonstration systems. This information is available at the GDE, Systems World Wide Web site (URL: http://www.gdesystems.com/MPS/SlipSheets/ATIMS.html). The system has been demonstrated on Apache, F-14 and B-1B.

The ATIMS project is developing tactical information management and cockpit automation technology to reduce pilot workload, reduce systems avionics cost, enhance operational flexibility, increase mission effectiveness and increase survivability. ATIMS will provide enhanced flight situation awareness, information for alternative mission selection and more responsive unit level mission planning and rehearsal. The ATIMS program consists of a four phase, multiyear plan that includes periodic technology risk reduction demonstrations, integration of new technologies and incremental technology insertion. Among the technologies included are advanced panel and helmet displays, high density electronics, digital data links, automated planning, data compression, aircrew interface techniques, data visualization techniques, multi-level security and commercial open architectures. The project needs to demonstrate advancements in-flight tests every year.

Large, fast data storage is a critical technology for this program. As part of the mission planning function, while on the ground, the pilot uses a helmet mounted display and a data storage device to plan and rehearse the mission. That same data storage device is then taken on the plane to provide mission management, situation display aids, in-flight replanning and even embedded training. During the mission, the data storage device also needs to record all the signals and information coming to the pilot which is then replayed during mission debriefing. Thus the data storage device needs to be removable and rugged. It is critical in the pre-flight stage, during the flight and post flight. This concept is illustrated in Figure 3 which comes from the GDE Systems, Inc. corporate web site,

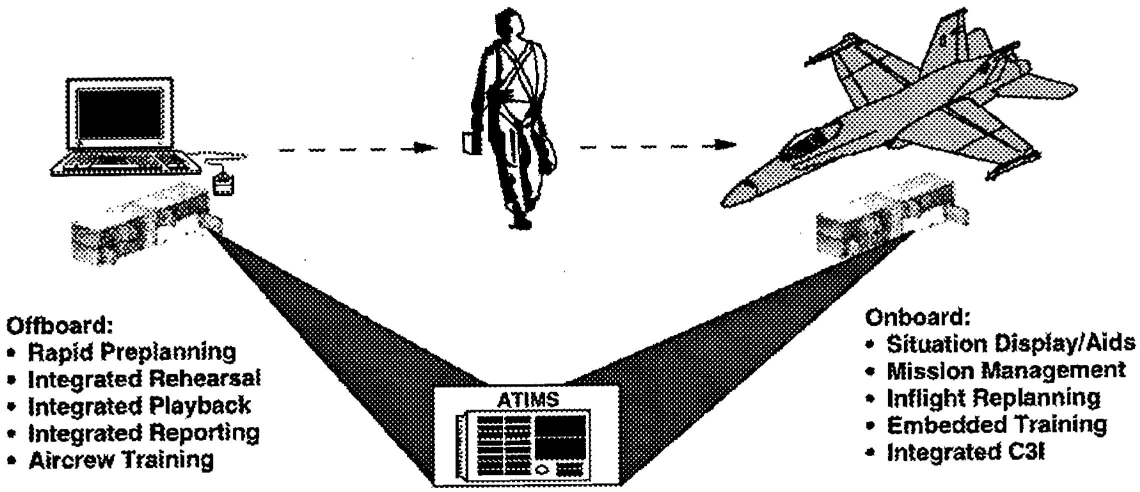

Figure 3 ATIMS Features (from GDE Systems, Inc.)

referenced above. Current system demonstrations are being performed with an optical drive from Mountain Optech that holds 2 gigabytes. A 4 gigabyte drive is needed now, and anticipated needs run to 8 gigabytes in 1998, 16 gigabytes by 2000 and a full 32 gigabyte device by 2002. The customer ultimately wants a solid state device (i.e., no moving parts) but a rotating optical disk could be appropriate for the 1998 demonstrations. The device requires low access time and fast data transfer rates. We have unfortunately been unable to quantify this important parameter although program personnel used the word "instantaneous". Among other important requirements for this device are ruggedness. It needs to survive up to 15 G. The size form factor for the device is around 8"×10"×5". Another critical feature is it needs to be removable and the data destructible in-flight. Hence, erasability of the information is a critical feature that two-photon memory materials could bring to the program.

Over the next few months this program will be demonstrating its usefulness to the Army, Air Force and Marine Corps. Program personnel claim to have visibility up to the highest level of the Pentagon. They have expressed a great degree of interest in the Call/Recall technology and in fact would like to meet with Call/Recall personnel. The Boeing program personnel feel that it would be worthwhile to set up a meeting with the prime contractor, GDE Systems in San Diego and would be interested in performing a demonstration of the Call/Recall technology in the ATIMS program.

3.7 F22 and JSF

These two programs for next generation fighters are discussed together here due to their similarities. Both are in the development stage and the F-22 which is further along this path has been used as a baseline for much of the JSF (Joint Strike Fighter) design work. Of course, the two fighters have very different missions. The F-22, Advanced Tactical Fighter, is intended as a replacement for the F-15. It is to be the air superiority fighter of the 21st century with a primary mission of air superiority, that is airplanes are its primary target. On the other hand, the JSF is primarily an air-to-ground fighter with land targets as primary. Both will carry air-to-air missiles and some air-to-ground weapons. While the F-22 is strictly an Air Force plane, the JSF, is as its name implies, intended for more services. The Air Force needs a low cost, multirole replacement for the F-16 and A-10. The Navy is looking for a first-day-of-the-war survivable strike aircraft to replace the A-6 and F-14 and the Marine Corps needs a Short Takeoff/Vertical Landing (STOVL) aircraft to replace the AV-8B and F/A-18. Also, the United Kingdom Royal Navy needs a STOVL aircraft to replace its Sea Harrior. As such, the JSF needs to be deployable on aircraft carriers, a particularly harsh environment for airplanes. Boeing is part of the Lockheed-Boeing team selected to build the F-22. Among the Boeing responsibilities is the avionics integration and the training system. This training system and its use of CBT was discussed above.

The F-22 program is currently in E&MD with the first flight of an E&MD aircraft scheduled for mid-1997. However, it is felt that, even though the final design was approved in 1995, the program will probably need to do a redesign in 1998 because some of the technology that was selected in 1992 is no longer available. This may impinge on the production schedule expected to run from 1998-2012. The JSF development is not as far along. Proposals have been submitted (by Boeing and others) to the JSF Program Office to build and flight-test the airplane. A concept-demonstration contract is to be awarded in November 1996 resulting in two companies being selected to build two designs of the JSF. The concept development should run through 2000 with E&MD planned for 2001-2007. Lessons learned during E&MD of F-22 will enable improvements on JSF. Based on the F-22 experience, JSF will probably need to examine current technology again in around 2005.

It has proven to be quite difficult to obtain information about F-22 and JSF, particularly F-22. For some reason, the program personnel tend to be quite secretive even with unclassified information. In particular, one document, describing the F-22 baseline architecture was prepared by the JSF program office distributed with F-22 approval. This is significant to JSF since the F-22 avionics architecture is the baseline for the JSF architecture. The F-22 program apparently withdrew their approval for JSF to distribute this document. In addition, during a large part of the period of performance of the present contract, JSF personnel were unavailable because they were preparing the proposal. Eventually, we were able to talk with some people to obtain the following information on needs for storage on these two aircraft.

One prime area for improved technology is for recording. F-22 plans to use an airborne video tape recorder (AVTR) to record mission data. The current system allows recording of only 2 hours of data (about 2 gigabytes) on 8 mm tape. The tape recorder multiplexes data from the pilot's HUD (Head Up Display) and a video camera. This information is then played back during mission debriefing. Currently, due to AVTR limitations, only one frame-per-second is recorded. It would be desirable for 30 frames per second data to be recorded. In addition, of the four pilot displays, now only one or two can be recorded. It would be desirable to record all of them. This combined functionality could require up to 120 gigabytes for recording with a bandwidth of a few hundred Mbps. For this function, the JSF program is looking at using solid state memory instead of the tape. A less expensive solution might be more tenable.

Another tape recorder is being used on F-22 during EM&D flight This unit records from the data acquisition unit (DAU) that interfaces to the main avionics processors via a fiber-optic bus. The DAU records to two AMPEX DCRSi tape recorders that work in parallel at up to 800 Mbps for 28 minutes. The DAU also outputs to a ground-based computer for real time system performance monitoring. Due to the limitation here, not all the data can be stored. The total peak data rate into the DAU is 2400 Mbps, but due to the limited recorder data rates, the DAU must filter what it sends out to record, or the processor software must throttle the data into the DAU. It would be desirable to have a larger recording unit that would record the bus, network and processor information over the 2 hour flight. Currently the two AMPEX recorders provide 96 gigabytes of data. If all the data were collected, this could amount to hundreds of terabits of information. A similar functionality would be useful on JSF when it enters EM&D (2001-2007). There the requirements are only for up to an hour of flight time, but just recording traffic to and from the integrated core processor that has 100 ports operating at 1000 Mbps per port would require in excess of 10 terabytes. The concern in both cases becomes timely processing and analysis of the massive amount of data after each flight or laboratory session.

Map data on F-22 will be stored in mass memory consisting of about 256 megabytes of ROM. Growth requirements are assumed up to about 576 megabytes. These requirements for JSF are still evolving.

The program personnel felt that the most difficult problem to be overcome for using optical memory technology on these fighters is the packaging. The product would need to be ruggedized to withstand 9 G's. It would need to withstand the shock and vibration encountered landing on a carrier flight deck (JSF). There are thermal constraints to force heat away from the units. Normally these avionics systems use heat exchanger modules or even modules with liquid coolant running through boards. The form factor is another constraint. The desire is to keep to the same SEM-E electronic module form factor which is $5'' \times 6'' \times 0.6''$.

3.8 UAV

The need for surveillance and reconnaissance air vehicles continues and in order to minimize personnel risk there is an ever increasing interest in UAV's (Unmanned autonomous (or sometimes aerial) vehicles). Such systems are viewed as a less expensive alternative to some manned missions due to reduced costs allowed by elimination of systems required for human survival and interfacing. They are considered best for use in situations where it is desirable to avoid human risk or exposure such as politically sensitive missions, or extremely hazardous environments. There have been a series of such programs intended to validate the concept of survivable reconnaissance. There exists a large amount of useful information on these programs on the DARO (Defense Airborne Reconnaissance Office) Web site (URL: www.acq.osd.mil/daro/uav.html).

DARO is overseeing UAV development through several Advanced Technology Concept Demonstration (ATCD) contracts. These include the General Atomics Predator (previously referred to as Tier II, now called MAE for Medium Altitude Endurance), the Teledyne-Ryan system (previously Tier II$^+$, now CONV-HAE for conventional High Altitude Endurance), and the Lockheed-Martin-Boeing DarkStar (previously Tier III$^-$, now LO-HAE for Low Observable High Altitude Endurance). The Predator system has been successfully deployed in Bosnia, and the other systems are in various stages of the ATCD's. Boeing is involved in two UAV-related programs, the DarkStar vehicle and a ground station for mission planning for the General Atomics Predator.

The DarkStar vehicle is being developed for the Air Force by Lockheed-Martin with Boeing responsible for the avionics integration and autonomous controls. The DarkStar mission is high altitude stealthy reconnaissance (40,000 ft.) for flights up to 8 hours duration. Currently the DarkStar vehicle is limited in functionality due to cost limit requirements. This limits the system to one on-board sensor, either a SAR or an EO sensor. Flight testing continues in spite of the recent crash of one of the two constructed DarkStar vehicles.[29] The UAV environment is expected to be typical to other (piloted) aircraft, so requirements such as found in the MIL HDBK 5400, are appropriate goals. Most of the true numbers for UAV imaging requirements are not available, but through several data points we can set some limits and projections.

Program personnel state that currently imagery data are collected at a rate of one per second for 1000×1000 pixel images over the 8 hour mission. Other capabilities cited are coverage of 5×10^4 km^2 at 1 m resolution or 600 images of 4 km^2 areas at 30 cm resolution.[30] These numbers imply data collection rates of 20-40 Mbps. Growth is projected up to 500 Mbps for flights up to 24 hours. The data are transmitted down over satellite links at 1.5 Mbps, or straight to ground over the Common Data Link at a rate of 137 Mbps sometime in the future. With recording bandwidths higher than communications link bandwidths, if the sensors are to work at full capacity, there must be adequate storage on-board. Even without on-board storage, there must be storage at the ground station to handle all the transmitted information. Another possibility is for the sensors to take data at full capacity, to transmit at full capacity and record on-board the differential between what is coming in and what can be sent out. Assuming all the data at the 20 Mbps rate are stored on-board, this would require around 630 gigabits of storage, and the growth required to a maximum of 500 Mbps for 24 hours would require around 43 terabits. Looking at the ground requirements, the 1.5 Mbps link over 8 hours requires about 43 gigabits and the growth to 137 Mbps for 24 hours requires about 12 terabits. Finally, assuming data are being downloaded at the maximum rate, and only need to be stored on-board at the differential rate requires about 500 gigabits with growth up to 30 terabits. Of course this scenario represents a problem in that both writing incoming data and reading the data for transmission are desired simultaneously from the same storage medium. Some scheme for handling this simultaneous transfer would be necessary.

Another desire for UAV's is to allow much more processing of imagery on-board. This would minimize the communication requirements to the ground, and change the type of storage needed. Faster volatile or cache storage rather than slower nonvolatile storage would be necessary. The evolutionary path envisioned for UAV's requires more and more processing and storage on-board. This follows the evolutionary concept of the military theater for a desire to have instant access to more and more information for battlefield planning. This leads to the concept of a distributed data base that would be accessed by multiple users. The distribution concept allows for redundancy for accommodate potential loss of individual storage nodes. The first stage would be on-board storage of reconnaissance data, which would become more and more complicated in time representing better and better sensors. Satellite imagery might be stored or uploaded for comparisons or correlations. In addition, to allow flexibility in planning, map imagery might be stored or uploaded to allow for change of the area of intent on the fly. Eventually, one hopes to arrive at ATR (automatic (or assisted) target recognition) and weapon assignment. Currently ATR is an unsolved research problem, but estimates are made that ATR capability would reduce communication bandwidths required for UAV's by factors up to 10^6. This would greatly decrease the cost of such systems.

3.9 DEMPC

Another UAV program that Boeing is involved in is the DEMPC (Data Exploitation Mission Planning and Communications) ground system for mission planning for Predator. This system currently uses three separate systems (one for data collection and two for mission planning) that contain 8 gigabyte disks. The data collection involves storing "video snapshots" onto video tapes at about 2 megabytes per second for about 20 seconds. This represents a fairly minimal requirement of about 40 megabytes. Map data for planning consists of a few maps such as DTED (Digital Terrain Elevation Data) of about 320 megabytes. More map data storage would be desirable, and the capability of full-motion video, not just snapshots would be useful. This could would raise the capacity requirements substantially. The main environmental concern for this deployment is dust. Used in a field station, where personnel are not paying particular attention to cleanliness, good sealing against dust is their prime problem now.

Program personnel are currently thinking about architectures for future systems, for five to ten years in the future. They project a need for up to 10 or 100 times more storage. Among the desired functions are more map data and more image processing. However, a big question in the whole UAV scenario remains as to how much processing is to be deployed on the vehicles themselves and how much is left at the ground stations. The answer to this question depends critically on how fast data can be moved around. Faster communication links might minimize requirements for on-board processing and put more demands on the ground station. This may also be a more cost effective solution, depending on how many UAV's are controlled by a given ground station.

3.10 Integrated Battlespace

There is a lot of thought going into the battlefield of the future and how wars will be fought and managed. This all comes under the area of "Battlefield Management". This is currently being looked at in terms of future business, rather than with any specific program requirements, but obviously uses inputs from specific programs now, such as specific sensor platforms, etc. There is much speculation on what will be required for the future battlefield, and all are in agreement that much more information will be available and will be desired. Typically data are collected and analyzed at one ground station; although as discussed above, there is some interest in moving to distributed data bases. Much of this information is imagery. Satellite imagery, and map data are two key components. Most of the information about satellite imagery resolution is not available, but we can use as an example SPOT imagery. For a typical UAV coverage area of 50,000 km^2, at SPOT resolution of 10 m, with 3 bytes per pixel, this gives image sizes of around 1.5 gigabytes. For the higher resolution of 0.3 m used on DarkStar, this number grows to 1.5 terabytes. Even for the smaller 4×4 km^2 image sizes, these still require 100 megabytes. Other programs discussed here are also concerned with map imagery. This includes any program involved with mission planning (DEMPC, ATIMS). Among people who work with the map data, there is much disagreement over how much there is, how much is available and how much is truly needed. For example, the US Army has expressed concern that there is uncontrolled appetite for map products and often users state their requirements improperly.[31] Although some of this is program dependent, there seems to be a general disagreement over whether data covering the entire earth would ever be useful. We have made several attempts to quantify how much map data is available or would be useful. This is difficult because generally DMA products are only available to DoD and contractors can obtain limited subsets. Due to varying resolutions and varying amounts of coverage, it is not completely straightforward how to estimate storage requirements for the maps. For example is stored in a differential format such that elevation differences are noted. Thus a fairly flat area, like an ocean would require much less storage capacity than an equivalently sized area that is mountainous. Another DMA product is the Digital Chart of the World (DCW) [31] giving information providing global coverage at a scale of 1:1000000. This number gives the scale, but we do not have the resolution for this data. The complete data set, however, requires 1.7 gigabytes on 4 CD-ROM disks. The DMA also provides other map data at varying resolutions. These are generally available now on varying numbers of CD-ROM's. One data user working on intelligence systems using relational database management systems has made some estimates of map data required. This includes about 1.6 gigabyte of map data for a given theater, 15 megabytes of planning data and 1 gigabyte of intelligence data. The estimation for all the world is 600 gigabytes of maps, 1 gigabyte of planning and 10 gigabytes of intelligence data. These numbers give us some feeling for the kinds of requirements that exist today and those that may arise for future needs.

3.11 Other Applications of Interest

Several other applications with potentially large memory requirements are currently being worked on within Boeing. These have not been looked at in detail in this study only due to lack of resources. They are briefly summarize here as worthy of future consideration for studies on requirements to drive technology development or to serve as field test programs for storage technology tests. Several of these are space-based applications. One of these is Space Station Freedom. Boeing is the prime contractor and responsible for the crew habitation modules. There is apparently some interest in on-board storage of maintenance data, CBT for the crew and even storage of books or entertainment data. Due to the extreme space limitations, maximum storage densities are desirable. Another space application is Resource 21, a commercial satellite remote sensing service being started by Boeing. Due to concerns about competition sensitivity, specific data on this system is unavailable, but it is likely to be on the same order as that for the many NASA remote sensing and satellite imaging programs. These easily generate multi-terabytes of data. Another possible area requiring large amounts of storage in the near future are the commercial satellite systems such as Iridium and Teledesic.

There are also a number of military programs that might have requirements or could serve as useful field test programs in the development of fieldable systems. These include both ground-based and airborne examples. One example is the ETRAC system, a field deployable ground station for processing U-2 sensor data. The sensor data currently is limited to the SAR payload, but U-2's can also carry EO-IR payloads which would generate imagery data as well. This system is currently limited in that it cannot retain all the imagery for a given period of operation. Faster, more compact storage could alleviate this problem. The ETRAC system is also being considered for use with both the Tier II^{+} and Tier III^{-} UAV systems due to their similarity to the U-2. Another ground-based application in the intelligence arena is that of the Air Operation Center that supports the Joint Force Air Commander (JFAC). This center gathers intelligence data and imagery to enable production of the air tasking order for the next day's missions. Currently this is ground-based, although there are concepts under development to make it air based. In its current configuration, it requires hours to handle the available data. One improvement the system could use is to be able to handle real-time modifications of data. This requires higher data rates and larger capacities. Finally, there is some work on AWAC's called the "Open System Architecture" (OSA), that is concerned with rehosting the AWAC's software and perhaps adding additional capabilities. Most of the interest is in the kind of map and satellite imagery data discussed above. Also, AWAC's training as discussed in the CBT section represents an area of interest. A potential airborne system is the Airborne Laser, a 747-based laser for destroying offensive theater ballistic missiles. This contract is to be awarded in November, 1996.

4.0 Technology Roadmap

In this section, we present a roadmap delineating the progress required to be made in two-photon memory technology over the next decade to fulfill the requirements documented above. We begin by summarizing the scope of the requirements found for the applications studied. We then discuss the various individual technologies required to develop a complete optical memory system. We discuss the current and projected improvements in these technologies, some to be done by Call/Recall or other Rome Laboratory contractors and some to be achieved in other markets. Finally, we conclude by summarizing this report.

Table II contains the summary of all the requirements documented above. We have attempted to gather all the pertinent requirements. The columns in the table contain: the application name, the type of memory needed, the capacity needed, the transfer rates desired, a description about the environment, and a description of the memory format required. Several applications have a few different functional requirements and we have attempted to list them all. We have used the maximum estimated capacities and bandwidths needed. The access times are not included since little information was gathered about this parameter. This parameter depends very specifically on the architecture, and degree of specificity needed was not available, but submilliseconds are likely. Very few programs were able to give definite information on the expected growth rate of requirements on a scale of years, so this table summarizes the projections for about 2005. In column two, for memory type, we assume ROM, WORM, and RWE (read-write-erase). We also include cache which is a short term RWE for frequent accessing. Most of the others RWE requirements only require erasing in the event of catastrophic mission failure. The capacity column uses the abbreviation G for gigabits and T for terabits. The environment column allows the categories of office, commercial airplane, Mil 5400, and >Mil 5400 (additional requirements beyond Mil5400). These are explained in more detail in the sections above discussing the specific applications. Finally, the format column includes the type of data such as multimedia, imagery or vectors. We have included the data type "stream" to describe what fundamentally consists of serial data such as arrives across a computer or network bus.

4.1 ROM, WORM and RWE

Examination of Table II shows that primarily three types of memory are needed by the programs reviewed. These are a ROM system holding up to hundreds of gigabytes or even terabytes, a WORM system holding the same amount of data and a RWE system holding equivalently large amounts. In addition, there is some demand for a cache system of lesser capacity, holding tens of gigabits. In looking at the functions and missions these storage devices are required for, we can make some other observations. Most of the

Application	Memory Type	Capacity (bits)	Bandwidth (bps)	Environment	Format
CBT	ROM, WORM, RWE, (cache)	100'of G to T, (10 G)	2×10^8	office	mutimedia, stream
ATM	WORM	!00's of G to 10's of T	10^4	office	imagery, stream
Flight Test	WORM	100's of G	10^8	commercial airplane	stream
VCX	ROM, (cache)	100's of G, (10 G)	10^9	commercial airplane	multimedia, imagery
B1-B	RWE	100's of G	10^8	>Mil5400, nuclear	imagery, stream
ATIMS	RWE	50 G	10^9	>Mil5400, high g, carrier flight deck	imagery, stream
F22/JSF	WORM	100's G	10^{10}	>Mil5400, high g	imagery, stream
UAV	WORM, RWE	10's of T	$5x10^8$	> Mil5400, high g	imagery, stream
DEMPC	ROM, WORM	10's of G	$5x10^8$	dusty office	imagery, stream

Table II. Summary of Application Requirements

RWE systems are required for missions of short duration (from hours up to a day). Typically they are used for crew debriefing upon returning from the flight. The erasability feature is only required in the case of "catastrophic mission failure" such as a crash into enemy territory. The WORM systems on the other hand, may be required for longer missions, such as the Flight test field station monitoring of up to months at a time. This information is required from days to months. Finally, the ROM systems are for longer storage, even up to archival. These observations can be used to help in the materials development planning.

4.2 Material Studies

Call/Recall is currently working on materials for all three of the storage types discussed above. Progress on material for a disk type ROM system is continuing with improvements in polishing and reproducibility. They expect to have a prototype ROM system, holding around 100 gigabytes in 2-3 years. Progress is slower on the WORM and RWE systems, with durability of written data one of the difficulties. Since the main

RWE applications are for shorter duration missions, the work on these materials should aim for shorter lifetimes, say 48 hours. Likewise, work on material systems for WORM devices should aim for midrange lifetimes, on the order of weeks to months. Material costs need to be kept to a minimum and ruggedness and survivability maintained.

4.3 Readout Devices

Another observation from the above table is that except for the one relatively low bandwidth application (ATM) the bandwidths needed range from hundreds of megahertz to gigahertz. The estimates for achievable bandwidths in both two-photon and holographic systems seem to be some of the most tenuous. They are cited as being primarily dependent on the speed of auxiliary readout devices, such as CCD arrays or a dynamic focusing lens.[13,17] For the most part, these estimates have not been demonstrated. Typically CCD's camera readout speeds are limited by their serial interfaces [2], and these are not at the kinds of speeds required by these applications. Other new technology that is appropriate for these tasks is currently under development, but not yet commercially available. These include flip-chip bonded arrays where each CCD element transfers directly to a local processor. Other new detector elements under the general category of "smart pixels", referring to hybrid silicon systems integrally packaged with optically sensitive materials are on the threshold of usefulness. These technologies should be monitored as providing possible solutions to the bandwidth problem.

4.4 Architecture Studies

Another direction to consider for bandwidth improvements is architecture studies. Many of the high bandwidth applications do not allow for a high degree of parallelism which is what usually contributes the most to high bandwidth. Instead, many of these systems are required to record serial data ("streaming") such as that from a network bus. Architectures to handle these types of applications need to be developed. Is there a way to make these inherently serial systems more parallel? The pulse collision mode of addressing is cited as being faster, but this is also further from a demonstrable system mainly due to the scarcity of inexpensive, high performance, femtosecond lasers.

In addition, architectures to allow near simultaneous reading and writing from the same memory element are necessary. These are required in systems like the DarkStar UAV which is recording information faster than it can be downloaded via its communication links. In addition, architecture studies for cache devices which are used in a different matter (frequent intermittent reads and writes) should proceed. Call/Recall is now working with some researchers on these kinds of studies. This is critical for video-on-demand and CBT applications.

4.5 Write Lasers

Another technology area that needs monitoring is that of write lasers. These are mandatory components for the desired WORM systems. These lasers have fairly stringent requirements to fulfill for working with the two-photon materials. McCormick et al.[18] list some of them. Included are: high peak powers, appropriate wavelengths, picosecond to femtosecond synchronization, high repetition rates, pulse to pulse energy uniformity and wavefront correction and intensity uniformity. The ones being used in demonstration systems now are inappropriate to consider for any portable or flyable system. However, these authors do cite a number of promising technologies for delivery of this kind of performance. These include diode-pumped self-mode-locked solid state lasers and amplified actively mode-locked semiconductor lasers. The progress of technologies such as these is crucial to the successful achievement of a viable WORM system and they should be monitored and supported.

4.6 Error Correction Codes

Coupled with the architecture studies must be work on error codes for parallel systems. Linear error code theory is quite mature and can be tailored to individual systems. The same needs to be true for two-dimensional systems in order to obtain the most improvement from this technology. In order to tailor the codes to the materials, the material BER studies, and channel models need to be pursued.

4.7 Packaging

The applications where ROM devices are most needed also happen to be those with the most benign environments, requiring the least packaging and ruggedization. These are ground-based systems, in office type environments. These are the applications most suitable for early field tests of the ROM prototype device, and the WORM or RWE as they are developed. More packaging and opto-mechanical design work will be required for flight systems. These will need to have minimal or no moving parts. Beam addressing and scanning will need to be done acousto-optically or electro-optically. The holographic system developed at Rockwell is reported to fulfill these requirements now.

4.8 Conclusions

We have presented a study of the utility of high capacity, fast storage such as that under development by Call/Recall, Inc. A review of the current state of storage technologies presents the well known gaps in storage types. These gaps are increasing as technologies develop at differing rates. For a large number of military and commercial systems, as well as standard consumer products, the computing limitation continues to be the memory technology. New promising types of memory under development have the potential to fill these gaps. Among the most promising are volume optical systems, including both holographic and two-photon optical. Later on, coherent optical techniques may become useful.

Among the many systems with a need for more and faster memory over the next decade are both ground-based and airborne. The CBT applications have some of the largest requirements, yet at the same time have some of the least restrictive operating environments. These are applications where initial fielded systems could be tried. They could have improved performance from the nearest to delivery product, the ROM device.

At the same time, material development is needed to perfect the writing capabilities of the two-photon materials. WORM devices represent a large segment of the program requirements, but the applications require shorter lifetimes than the ROM devices. This could help in the material development. Ultimately, the RWE devices are exceedingly important for future military missions. Once some packaging issues have been addressed, these systems can and should be flight tested on military jets. Both the ATIMS and B-1B program personnel have expressed interest in being involved in these sorts of tests. Bandwidth considerations remain a concern, but further architecture studies should help in this area. At the same time, further developments in auxiliary components such as writing lasers and readout devices are required. These components are being developed for other markets such as medical technologies and consumer electronics. As these markets drive the development, performance should improve and prices should continue to fall. The performance is important for military and commercial applications, but cost remains the overall driver. Improvements projected in the two-photon memory materials, the architectures and the auxiliary devices give every promise of this technology reaching a useful maturity over the next decade.

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Appendix

This appendix contains brief discussions about programs that were examined, but for one reason or another, found not to be suitable for continuing in this study. It is included for completeness.

VCX- C32A

This program is to provide a new Air Force 2, executive airplane for the vice-president and other high level government personnel. This program has fairly limited requirements, such as low data rates and no real need for video. The "office in the sky" concept having computers, printers, FAX's will require one file server with about 4 gigabytes online. The natural extension to this program, the SAMCOM's systems as discussed in the main text have much more challenging requirements. The time frame on C32A is that proposals have been submitted and up to six aircraft are to be delivered in 1997, so the time frame is also not useful for this study.

ECIT

ECIT stands for Electronic Combat Integrated Test. Boeing is serving as the system integrator/ prime for an upgrade to this system which consists of a ground-based testbed facility for simulating radiation threats to aircraft such as the B-2 or F-15. Tests can generate up to terabytes of data at bandwidths up to hundreds of Mbps. It is currently bandwidth and capacity limited by the RAID technology in use but is on a very short schedule and has severely limited funding. The operational date of 1998 for the upgrade leaves no opportunity for insertion of 3-D optical memory.

AST

The Airborne Surveillance Testbed (AST) has an infrared sensor housed in the cupola atop a Boeing 767-fuselage and supports development and evaluation of defensive systems to counter intercontinental and theater ballistic missiles. This is a ten year old program that continues on a yearly basis. This program could use enhanced data storage capabilities for both in-flight scenarios and for longer term storage. They are currently record limited since they can not store all the data they can obtain in real time. However, the program is a one-of-a-kind platform and they do not envision that any more will be built in the future. The lifetime of this current program is not well known either. Thus, although the program could have substantial needs for the 3-D optical memory, it is not in a good position to serve as an example of a real future customer.

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