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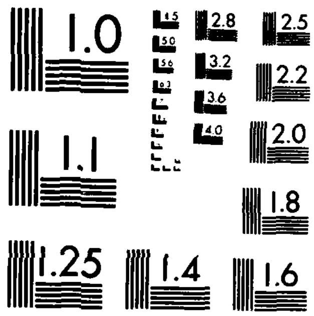

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ACQUISITION COST ANALYSIS FOR THE NEAR TERM MILITARY APPLICATION OF LASER VS MILLIMETER WAVE FOR SATELLITE CROSSLINK COMMUNICATIONS

THESIS

Presented to the Faculty of the School of Engineering

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Master of Science

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Preface

As the Air Force moves into the realm of space operations, it is finding the cost of doing business exceptionally expensive. Yet, the demand is there for space operations, to conquer space as we did the air, to perform the missions that can only be done from the "high ground." The situation is not unlike the basic economics dichotomy of the choice between "guns" and "butter." Today some of the "guns" are multi-million/billion dollar space systems which are vital to the United States' worldwide communication, weather, navigation, and surveillance capabilities; the "butter" is the public demand for lower taxes and increased government aid. The dichotomy is real, as is the fight for limited tax dollars. Therefore, it is essential that the greatest possible utilization be made of the dollars available, this is especially true for space operations.

For years I have been interested in communications and electronic warfare. In recent years I followed these areas of interest as they have moved swiftly into the space age. The move into space brought with it a demand for improved (and expensive) technologies in order to have systems that were small, light, used very little power, and had long lives in the hostile environment of space. In the area of communications, especially digital, computer to computer communications, user requirements were for ever increasing data processing rates. Evolving out of the communications efforts were two competing technologies, millimeter wave and laser. Both technologies can improve communications capabilities, but each technology has its own inherent capabilities and limitations. As a result, there seemed to be an expensive competition for R&D dollars to exploit both technologies. The question facing this study was, "Is there one technology which can be chosen to proceed ahead, while eliminating the other from competing for the limited dollars?"

In this study only one factor, procurement cost, is analyzed to determine whether there is a clear choice between millimeter wave and laser technologies in their application to satellite to satellite crosslink communications. To adequately study even the limited topic of procurement costs for satellite crosslinks, required extensive help from laser, millimeter wave, satellite communications, and costing experts. Without these experts graciously volunteering their time and talents, the study would not have progressed beyond the literature review phase. For their expertise help and personal encouragement, I want to thank Vincent Chan and Bill Ward at MIT Lincoln Laboratory, Young Lee at COMSAT Corporation, Jim Merritt at McDonnell Douglas Astronautics Company, John Chitwood at

NASA Goddard Space Flight Center, Larry Zapone and Gary Wimberly at AF Systems Command/Space Division, and Donna Vogel at AF Systems Command/Aeronautical Systems Division. I wish to recognize Air Force Institue of Technology professors Dr Joseph Cain and Dr Theodore Luke for providing the initial direction and continuing advice. Finally, I want to thank my wife, Dorothy, and father-in-law, Ellwood Hill, for their part in putting this paper together.

Contents

<u>Contents</u> (continued)

List of Figures

List of Tables

Abstract

Two alternative satellite communication technologies have evolved independently of each other and now seem to be in direct competition for limited R&D dollars. In an attempt to identify which technology is best, this study concentrates on one aspect of satellite communications - intersatellite crosslinks which are capable of processing 1 to 10 megabits of data per second. The analysis effort is further limited to comparisons of procurement costs and factors which influence these costs. The RCA PRICE Model is used to estimate costs of crosslink subsystems. Extensive review of the literature, as well as design estimates from experts is necessary to provide the PRICE Model with sufficient details to produce a credible cost figure. A modified Delphi method is used to aggregate the estimates of the experts. From the cost comparison of laser versus millimeter wave crosslink systems, it seems that millimeter wave with its more mature technology has the cost advantage. However, as laser technology reaches a level of maturity close to that of millimeter wave, the difference in procurement costs should become minimal. There are eleven technical, operational, and cost factors which must be analyzed to adequately determine which technology is "best." Procurement cost analysis by itself does not determine which technology should be continued or stopped.

ACQUISITION COST ANALYSIS FOR THE NEAR TERM MILITARY APPLICATIONS OF LASER VS MILLIMETER WAVE FOR SATELLITE CROSSLINK COMMUNICATIONS

I. INTRODUCTION

Background

Journal articles and published studies on millimeter wave (MMW) and laser applications seem to indicate that two alternative communication technologies have evolved independently of each other. As such, a lot of money is being spent on both technologies to accomplish the "same" job. The question facing the Air Force is whether one technology has a clear advantage over the other, considering cost and technology factors. If this can be determined, the result will be enormous savings in valuable research and development dollars by eliminating one technology and proceding further with the other. Air Force managers who are not familiar with both millimeter wave and laser technologies, may be asked to support one technlogy over the other for future satellite crosslink applications.

Applications of the two technologies in the field of satellite communications is seen as a means of overcoming the current problem of overcrowding of the radio frequency (RF) bandwidths and the inadequacy of carriers to handle high data rate signals. Both MMW and laser technologies allow for a tremendous improvement in the number of frequency channels available and useable bandwidth for high data rate flow. When compared to other current technologies, both MMW and laser can do the job with less weight, power, and size penalties. Both are capable of handling data rates in excess of one megabits per second (Mbps); both employ narrow beams and have substantial atmospheric attenuation to combat problems from interference and enemy electronic jamming. Due to the relatively short wavelengths used in both technologies, components tend to be relatively small. With the use of solid state devices the power requirements are within satellite constraints. Efficiencie are improving and are well within satellite tolerances (for heat removal). By using redundant components and the right selection of materials, reliability can be maintained over the 7 to 10 year operational life of a satellite. However, what can be said about MMW's improvement over current microwave systems might also be said for lasers over MMW. Laser systems, versus MMW, can have wider bandwidths to handle much higher data rates. Also, the laser's narrow beam and monochromatic properties allow a greater number of user channels to operate within a relatively small geographical area without mutual interference. Why then is there competition; why are lasers not the clear choice; why are millimeter wave systems a consideration at all? (9:2;29:16, 63;31:349-359;32:38-43;59:1)

The choice between MMW and laser systems is influenced by operational and practical factors. To begin with, to explicitly define which technology is best would require a comprehensive analysis which would consider mission requirements, data rate requirements, component capabilities, total subsystem weight, subsystem power requirements, satellite real estate and sweep volume available, subsystem/component moments of inertia, attitude reference accuracy impacts, reliability, operational life, subsystem ranging and timing requirements, non-rigid body vibration tolerances, environmental survivability, and acquisition and operational costs. (1:204;27:2;42:127,128;46:21)

Problem Statement

Air Force managers who may be unfamiliar with technical and cost aspects of millimeter wave and laser crosslink capabilities and limitations, will be asked to provide support for development of new crosslink systems. These managers need to know whether millimeter wave and/or laser technologies meet validated Air Force communications requirements, including those for countering electronic countermeasures. Assuming either technology can satisfy nearterm (5-10 years) requirements, can one technology be chosen based upon acquisition costs? If a cost effective technology can be defined, what are the key factors that could influence/cause the Air Force to switch support from one technology to the other?

Scope

The study concentrates on satellite crosslinks for military applications in the nearterm (no more than 10 years). Cost analysis is made via the RCA PRICE Model which requires identification of possible components and subsystems by weight, volume, degree of manufacturing complexity, and when possible, known costs.

To make a cost comparison of laser and MMW systems, it is necessary to define a regime where both systems can perform equally well. For this study the common ground will be based upon data rate capability of 1 to 10 Mbps, for a geostationary system made up of four satellites with an on-orbit life of 7 to 10 years. The generic MMW crosslink is specified to operate at 60 GHz. The stated generic characteristics fall within stated Air Force objectives for MMW and laser communications developments. (It must be noted, although this regime provides common ground to make comparisons, it also excludes regions where one system may have a clear technical advantage over the other. Some of these "regions" are identified in Chapter II.)

Assumptions

Three major assumptions are made in this paper. First, the RCA PRICE Model provides an unbiased comparison. That is, cost factors used by the model will have errors of the same magnitude and direction for laser and MMW space subsystems. Second, the experts currently involved in designing or manufacturing a satellite crosslink system, provide answers closer to the "true" values for hardware and component portions of the crosslink questionnaire (described later) than do experts working only with the technology issues or a specific subsystem. Third, no extra radiation protection is built into the crosslink. Thus, increased hardening to meet possible military requirements will be built into the satellite's outer structure, not the crosslink itself.

General Approach

(1) Through review of available technical literature it is determined whether laser and/or MMW technology can meet military crosslink requirements.

(2) Technical literature provides technical inputs on weights, volumes, reliability, key technologies, and an occasional known cost, all of which are the basis for the design of generic laser and MMW crosslinks.

(3) The generic designs are validated and updated through questionnaires sent to crosslink experts at MIT Lincoln Laboratory, Aerospace Corporation, McDonnell Douglas Astronautics Company, Communication Satellite Corporation, National Aeronautics and Space Administration, and Air Force Systems Command/Space Division.

(4) Generic system's production cost data obtained through runs on the RCA PRICE Model.

(5) Analyze RCA PRICE results versus estimated costs

provided by experts who answer the crosslink questionnaire.

(6) Vary input parameters to the RCA PRICE Model to determine how sensitive costs are to potential changes.

Sequence of Presentation

The remaining chapters and sections of this report are organized to provide the reader with sufficient background to understand better the problems associated with the choice between MMW and laser crosslinks. This is provided in Chapter II through an extensive review of highlights of current writings on the related subjects. (Additional background on MMW and laser technology is provided in Appendix A and B, respectively.) In Chapter III the reader is then introduced to the RCA PRICE Model and how it was used in this study to provide a cost comparison between laser and MMW crosslink systems. Also presented in Chapter III are results of cost comparison runs based upon inputs from the experts, as well as a series of runs based on changing the original inputs to determine the effects on acquisition costs due to decision and technological changes. In Chapter IV a discussion of results and conclusions is presented based upon the results of Chapter III and findings derived from the literature review in Chapter II. Chapter IV concludes with recommendations for further study and Air Force actions. As mentioned above Appendix A and B contain additional technical material on lasers and MMW crosslink systems. The RCA PRICE Model data worksheets are presented in Appendix C and copies of the crosslink questionnaire in Appendix D.

II. LITERATURE REVIEW

It was necessary to review a large number of documents on millimeter wave, lasers, crosslinks and the associated technologies in order to develop the necessary degree of technical understanding to identify generic crosslink systems and to provide the RCA PRICE Model with reasonable input data. The review played such an important part of the overall study that this entire chapter is devoted to the pertinent information derived from sources listed in the bibliography. The chapter begins by defining what crosslinks are and their value to the military. Then the review becomes more technical as the reader is introduced to millimeter waves and the role millimeter wave technology plays in the development of a satellite crosslink system. Out of the MMW section comes the generic design used as the basis for the crosslink questionnaire. The MMW section is followed by a parallel effort on laser technology. The chapter concludes with some views which answer the question of how to choose between MMW and laser crosslink systems.

Crosslinks Defined

In terms of satellite communications, crosslinks, also known as intersatellite links (ISL), are those links which connect one satellite with another. One satellite may have multiple crosslinks to one or more satellites. The type of data passed through these links are mostly digital data and satellite command and control (known as tracking, telemetry and command or TT&C). Data rate requirements vary from a few kilobits per second (kbps) to several gigabits per second (Gbps).

Characteristics of a crosslink depend extensively on the carrier wavelength. As stated in Chapter I, crosslinks must be capable of handling high data rates; this corresponds to shorter wavelengths able to provide greater bandwidths. Another necessary characteristic is the capability to be free from interference and electronic countermeasures (ECM). Here again shorter wavelengths mean narrow beamwidths and atmospheric attenuation, both of which are good weapons against interfence and ECM. Considering that the system must fit into a satellite, it is necessary for the crosslink to be small in volume and weight, require minimal power, be highly efficient, and be reliable over a 7-10 year on-orbit life. With these characteristics, wavelength plays a mixed role. Associated with shorter wavelengths are smaller components with shorter operational lives and less reliability. (21:19;55:4,5;59:9)

Crosslink Requirements

Today's command-control-communications (C^3) is highly vulnerable to disruption, sabotage and direct attack. A large part of this vulnerability is due to our C^3 structure relying upon commands and digital data being relayed via satellite through overseas ground stations. Satellite crosslinks can circumvent some of the C^3 problems by eliminating the need for highly vulnerable ground relay stations outside continental United States (CONUS). (29:1,16)

Crosslinks provide the added promise of increased flexibility, improved responsiveness, and enhanced C^3 electronic countermeasure (ECM) resistance. Flexibility is increased through expanded distances over which communications can be maintained. Likewise, increased flexibility is provided through augmented choices of satellite "tie-ins," where the user is not restricted to a small number of communication satellites but has available a large number of satellites connected by a crosslink intersatellite network. Using crosslinks it is possible for reconnaissance systems located anywhere in the world to have collected data relayed in near real time(1) directly to the necessary command, control, communications, and intelligence (C^3I) center. Rapid Deployment Forces (RDF) can deploy to remote areas and almost immediately have necessary communication links. Crosslinks increase connectivity providing the possibility

(1) Near real time refers to data sent as quickly as it is received with minimal processing delay.

of alternate paths to get around interference and enemy communications jamming. Electronic counter-countermeasure[2] (ECCM) is further enhanced by having more flexibility in locating satellites. This allows selection of orbital locations with a more favorable satellite-ground station geometry for friendly forces which is less favorable to enemy forces. (54:4-33;55:4)

Crosslink applications include several categories by range and function. Long links that span 40 degrees in orbital separation can provide connectivity between regional or transoceanic satellites. For smaller separations (3-40 degrees) crosslinks can provide connectivity between an earth station and a remote satellite. Another application of crosslinks involves communications within a cluster of satellites, all within 50 miles of each other. The cluster could be handled by a single ground station with communications to specific satellites handled through an intersatellite network employing high data rate crosslinks. (37:E.1.3.1;55:2.7;59:11)

Although most of the current efforts are for geosynchronous orbit to geosynchronous orbit crosslinks, there are applications for relaying commands and data to and from vehicles in space, low earth orbit satellites, and aircraft in the atmosphere. (54:1-10)

(2) ECCM refers to fixes that allow electronic devices to overcome jamming or other countermeasures.

Crosslink History

In January 1975, radio amateurs successfully demonstrated an intersatellite link from AMSAT/OSCAR-7 to AMSAT/OSCAR-6. The antenna systems of these small satellites were essentially omnidirectional. An uplink signal sent to OSCAR-7 at a frequency of 432.15 megahertz (MHz) was relayed on the 145.95 MHz downlink. Some of that signal got into the uplink receiver of OSCAR-6, where it was repeated at 29.5 MHz on the downlink. There was no necessity for the satellites to track their received signals in angle, frequency, or timing since both satellites carried linear transponders and both were in nearly identical circular polar orbits. This crosslink was available whenever the phases of the satellites put them in view of one another. (56:1;59:12)

A significant step forward in the demonstration of crosslinks was taken during the testing of NASA's ATS-6 satellite. In April 1975, data was relayed from the near-Earth polar orbit geodynamics satellite GEOS-3 via an S-band (frequencies from 2 to 4 gigahertz(GHz)) uplink to ATS-6, followed by a C-band (frequencies from 4 to 8 GHz) downlink to a ground terminal. GEOS-3 carried four low-gain antennas. Of these four antennas the one which pointed closest to ATS-6 was selected by ground command. Next, in June 1975, the sun-synchronous weather satellite NIMBUS-6 demonstrated S-band/C-band data relay through ATS-6. The link was maintained continuously during the ATS-6 pass in order to keep its 1 degree beam/30 foot diameter paraboloid antenna (at 2.25 GHz) pointed to within 0.1 degree of the line-of-sight to the low altitude GEOS-3 satellite. The S-band monopulse feature of ATS-6 allowed autotracking the uplink signal. (56:1,2)

A pair of crosslinks were operated in July 1975 as part of the Apollo-Soyuz Project. In this case the high-gain antenna on the Apollo Service Module in its low-altitude inclined orbit was pointed toward the geostationary satellite ATS-6. As before, the entire ATS-6 had to be pointed toward the Apollo spacecraft to maintain proper antenna orientation. This system worked very well, providing two-way communications and data relay for 55 minutes of each 87 minute Apollo orbit. (56:2)

On 15 March 1976 Lincoln Experimental Satellites 8 and 9 (LES-8/9) were boosted into orbit. The project sponsored by the U.S Air Force and Navy carried a pair of millimeter wave crosslink systems into geosynchronous orbit. The initial concept included the use of both a laser and 55 GHz intersatellite links. However, it was felt that these two technologies were too high-risk at the time, so it was decided to build the crosslinks in the same 36-38 GHz band as the uplinks and downlinks being designed for LES-8/9. Lincoln Laboratory's effort differed from earlier crosslink experiments in that LES-8/9 could acquire and track the other crosslink without interfering with other systems on the satellite (eg., since LES-8/9 had its own crosslink antenna the satellite did not have to be rotated to employ the downlink/uplink antennas for the crosslink communications.) (56:1-5) For the past seven years LES-8/9 have been operated successfully, demonstrating a true intersatellite crosslink capability which had minimal impact on the primary mission of the host spacecraft. LES-8/9's success has borne out the promise of crosslinks for enhancing the flexibility and the survivability of military satellite communications. (56:7)

Crosslink's Crossroads

Today, two technologies vie for the future of crosslink business, MMW and laser. When compared to other current technologies, both MMW and laser can do the job in smaller, lighter packages and at higher data rates than any of the previously designed crosslink systems. Both are capable of handling high data rates; both employ narrow beams and have substantial atmospheric attenuation to combat problems from interference and enemy electronic jamming. Due to the wavelengths used in both technologies, components are relatively small. With the use of solid state devices the power requirements are well within satellite constraints. Efficiencies are improving and are well within satellite tolerances (for heat removal). By using redundant components and the right selection of materials, reliability can be maintained over the 7 to 10 year life of the satellite. (29:16,63;31:349-359)

Before a choice can be made between these competing technologies one must first understand what MMW and laser represent.

<u>Millimeter Wave Review</u>

Due to conflicting definitions of what is meant by MMW, it may be helpful to define how MMW is used in this paper. Figure 1 on the next page depicts the MMW region of the electromagnetic spectrum. The region spans the frequencies of 30 to 300 gigahertz (1 GHz = 10^9 hertz), corresponding to 10 to 1 millimeter wavelengths, respectively. This region may also be referred to as extremely high frequency (EHF) and the Ka bands. In contrast lasers are normally thought of in terms of optical frequencies and wavelengths with frequencies about 1000 times higher and wavelengths 1000 times shorter than those of the MMW region. (The distinction between MMW and laser is not totally clear since certain lasers operate in the MMW region.) (26:1)

Early investigation of MMW frequencies was stimulated by studies in molecular spectroscopy and military radar developments. In the 1950's the Bell System developed a communication system at EHF frequencies but discontinued this effort when the first laser became operational. (19:15) In the following years emphasis was placed on the development of the optical range of the electromagnetic spectrum and millimeter waves were practically disregarded. However, when difficulties were encountered with the use of optical

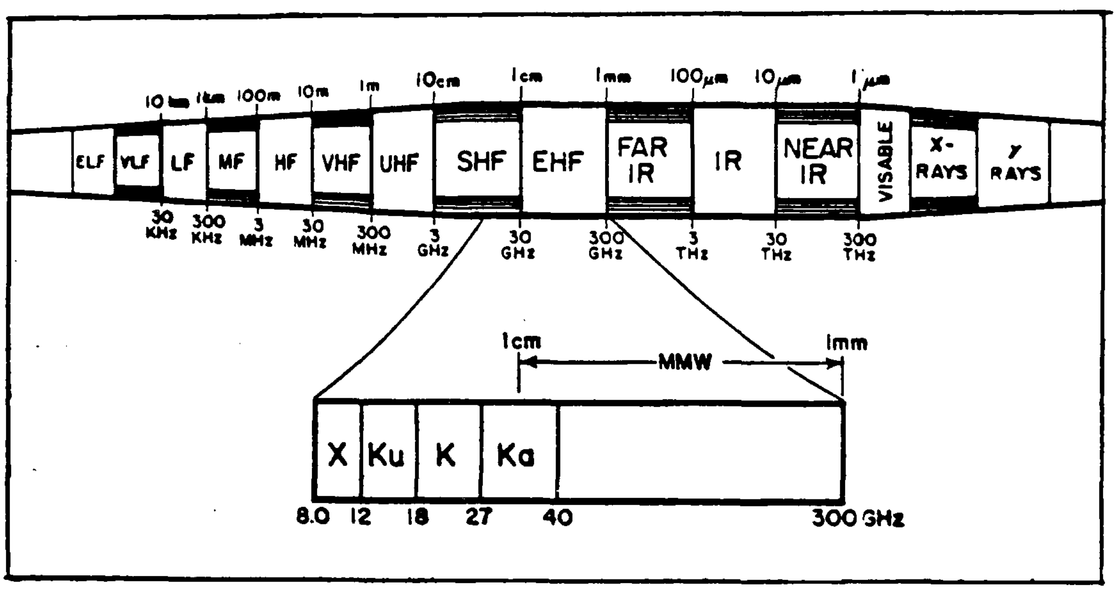

Figure 1 - Electromagnetic Spectrum

systems (due to limitations caused by fog, smoke, and dust), the situation changed drastically. That is, millimeter waves were considered as substitutes for or complements to optical systems. (19:16)

Over the past five years many advances have been made in MMW technology. Now, oscillators, waveguide components, mixers, and detectors are commercially available although not in large numbers. Manufacturing of MMW components requires ultra-high precision fabrication, which adds to their price tag. Even with relatively high component costs and limited availability, total MMW component/system production is expected to climb to $56 million by 1986 from $11.2 million in 1976. (19:16)

Proliferation of ultrahigh frequency (UHF) networks throughout the world is causing serious mutual interference problems between communications satellites and terrestrial stations. Current United States' communication satellites operate in UHF (.24 to .40 GHz) and 8/7 GHz bands, sharing these bands with other satellite services and extensive terrestrial systems. Even with intensive frequency management on a global basis it is increasingly more difficult to coordinate frequency use. Also, crowding of orbital arcs is the result of increased number of satellites vying for geosynchronous locations. Along with the crowding, there is a growing requirement for increased bandwidth to support higher data rates and accommodate increased numbers of satellite circuits for mobile (military) users. (30:1)

This ever increasing crowded condition has caused satellite communication link designs to enter into higher and higher frequencies. The reason for the use of higher frequencies can be seen by looking at the advantages of going to MMW. MMW provides 5 to 10 times the available bandwidth of all the lower frequency bands combined. (A ten percent bandwidth at 35 GHz is 30% wider than the UHF band.) Greater bandwidth is needed to increase the number of system subscribers, to utilize higher data rate transmissions, and to employ high bandwidth communication techniques (i.e., spread spectrum). (19:27,28;36:58)

The frequency-gain relationship allows the use of high gain, narrow beamwidth antennas of reasonable size. This characteristic is advantageous as the increased gain offsets low power currently available in MMW solid-state devices. For satellite-to-satellite links the signal can be confined to a narrow cone and the sidelobe power can be effectively reduced by atmospheric absorption before it reaches the earth. EHF frequencies allow small spot-beam coverage (footprint) to decrease interference problems for satellite-to-earth systems. (19:28,29)

Any discussion of MMW must address atmospheric attenuation. MMW atmospheric attenuation has been studied to great lengths. From Figures 2 and 3 on page 20, it can be seen that attenuation varies significantly with frequency, atmospheric conditions, and the transmission angle through the atmosphere. If MMW communication systems are to operate in the earth's atmosphere, they must be able to overcome the characteristic attenuation. This takes a combination of increased power and judicious selection of operating frequencies. As can be seen in Figure 2, there are four dips or propagation "windows" where atmospheric absorption is at a minimum: 35, 95, 140, and 220 GHz. Operating in these windows requires the least amount of power for transmission over a given distance. Most MMW radios designed for use in the earth's atmosphere, operate near one of these four frequencies. (24:3-9;36:56)

MMW's relatively low attenuation in the vertical is a fact not unnoticed by communications planners. It is extremely important for satellite applications where available power is limited. An explanation for this is the signal only travels through the dense, moist portion of the earth's atmosphere for a relatively short distance. (36:56)

Taking advantage of the regions of maximum attenuation also makes sense for covert communications systems and in satellite-to-satellite crosslinks. For covert operations it is possible to limit the range at which a signal can be detected by using frequency to balance the output power with a given level of absorption. Therefore, effective employment of power versus frequency, along with MMW's narrow beamwidth, make it almost impossible to detect a MMW signal unless the receiver is directly between the transmitter and its intended receiver. For intersatellite networks it is possible to eliminate terrestrial background interference

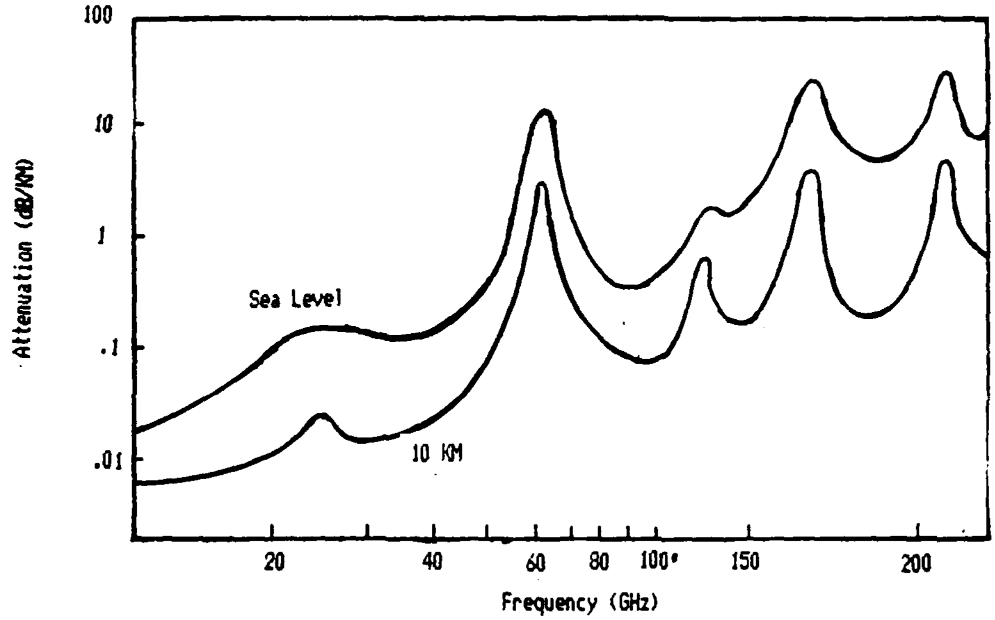

Figure 2 - Atmospheric Absorption in the Horizontal (Ref 36)

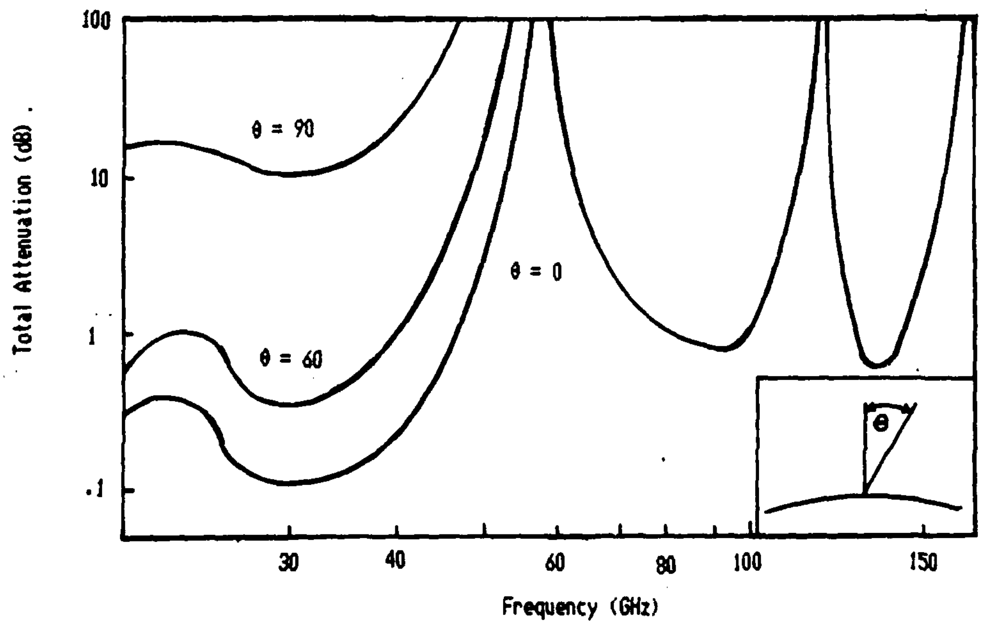

Figure 3 - Atmospheric Absorption in the Vertical (Ref 4)

by selecting a frequency at one of the maximum attenuation regions, say around 60 GHz. At the maximum attenuation frequencies, even at high elevation angles, attenuation is sufficient to effectively eliminate interference from sources at or near the earth's surface. (21:19;36:56)

Millimeter Wave Technology

A lot of DOD and NASA advanced communication satellite technology development is being focused on the EHF region of the electromagnetic (EM) spectrum. Air Force Systems Command/Space Division/YKX states that EHF technology offers the greatest potential payoff due to possible large band-width allocations (currently in excess of 1 GHz) and its inherent anti-jam features. Although there are many MMW systems being developed, there is only a limited amount of experience on actual hardware in space. Most military space communication technology at MMW frequencies was developed during the LES-8/9 proof of concept experiments. Other operational MMW equipment was developed for NASA's ATS-6 MMW propagation experiments, the Japanese CS satellite, and passive MMW radio astronomy sensors aboard a variety of satellites. (1:28,54; 34:1-10;56:5;59:20)

Air Force Program PE63431F, located at Space Division, has set out to develop proof of concept models for satellite EHF communications components. The goals of this program are to develop power efficient MMW components with 10 year operational life in a space environment. This effort is part of the Defense Communications Agency's architecture for 1980-1995. Expected results from this program should be seen by the late 1980s in a new generation of military satellites with greater anti-jam capability and increased communications for tactical and strategic users. By early 1990s expected results include survivable satellites with EHF communications in synchronous and non-synchronous orbits. (1:18,28,33;59:22)

In design of space communication systems, there are trade-offs to be made among signal power, antenna size, noise temperature, bandwidth and/or digital data rate. The generic MMW crosslink system depicted in Fig 4 (on the next page) takes these trade-offs into consideration and is the result of several studies referenced below, and refined by inputs from the "experts" who answered the crosslink questionnaire.[3] Each of the boxes is composed of complex electronic packages, connected by MMW waveguides. (9:2;11:28;20:4-17;51:428)

The overall system characteristics of the generic crosslink are: (1) weighs about 300 pounds, (2) requires 130 watts of power, (3) transmits 4 or less watts of RF power, (4) has a data handling rate of 1-10 megabits per second (Mbps), and (5) uses a 36 inch or larger cassegrain antenna to transmit and receive a 60 GHz signal with a

(3) Discussion on the questionnaire will be at Chapter III.

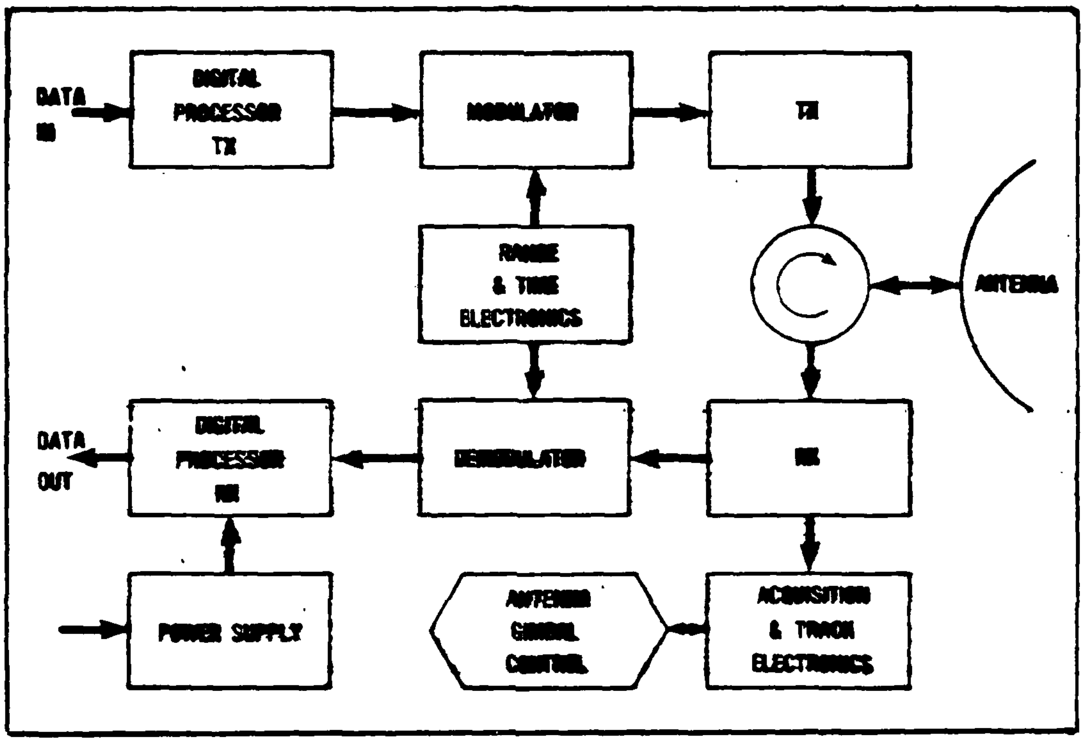

Figure 4 - Generic MMW Crosslink System

beamwidth of 0.4 degrees and 52 dB of gain. The generic crosslink would be capable of scanning 104 degrees in plane and ±10 degrees out of the orbital plane, using sequential lobing to angle track the adjacent satellite's crosslink. (9:2;11:28;20:4-17;29:65)

Laser Review

Optical satellite communication systems can be an attractive alternative to MMW military satellite communications, particularly when high data rates are required (ie., data rates in excess of 10 Mbps). Small antenna aperture is a main advantage optical systems have over MMW. At data rates above 10 Mbps optical systems gain a weight advantage over their MMW counter-parts. (11:3-7;13:1;31:349)

Air Force laser communication efforts have focused on a long-term technology goal. This goal is one of ensuring the availability of appropriate laser system technology to resolve communication problems expected to arise during the next two decades. The Air Force program is directed toward three principal applications: low data rate (less than 100,000 bits per second) systems for teletype/telemetry; moderate data rate (10^3 to 10^8 bits per second) systems for voice and computer-processed data; and high data rate (10^8 bits per second or greater) systems for extremely wideband transmissions. Spin-offs from the high data rate technology are expected to provide a survivable communication crosslink for satellite programs by the late 1980s. The low data rate technology offers a possible follow-on alternative (late 1990s) to present systems and also a capability for jam-resistant aircraft/satellite and satellite/satellite telemetry. The high data rate technology offers a survivable, wideband, multi-channel crosslink. (53:91-96;58:3;59:24,25)

The feasibility and utility of laser communications have been discussed since the laser was first demonstrated in 1960. The Air Force Avionics Laboratory was actively investigating laser communication system concepts by 1965, and in 1970 the Laser Communication Program was established. The goal of this program was to create a one gigabit (10^9 bits per second) laser communication system for space applications by 1980. That goal expanded communications bandwidth approximately two orders of magnitude beyond any other system then envisioned. After 10 years of dedicated effort and numerous budgetary restraints, the Air Force successfully demonstrated a one gigabit with an airborne system in 1980. (53:91-96;58:4;59:25)

From 1978 to 1980 the Air Force ran far-field acquisition and tracking tests at White Sands Missile Range in New Mexico. This program had some success on air-to-ground tests. (48:2;59:25)

Another action taken in the 1970s which led to today's capabilities was the Air Force's decision to develop laser communication systems based upon a frequency doubled Nd:YAG laser. Nd:YAG lasers, compared to carbon dioxide lasers, are easy to modulate, employ simple detection techniques, and are more efficient. (48:2)

Since the first decision to go with Nd:YAG lasers, lamp-pumped and sun-pumped Nd:YAG lasers have been successfully developed and operated. A space-qualifiable prototype lamp-pumped laser has demonstrated an output power of 330 milliwatts, 400 picosecond pulsewidth, and a pulse repetition rate of 5 X 10^8 pulses per second. A similar sun-pumped laser has been developed with an output power of 400 milliwatts. (Responses on the crosslink questionnaire reflected more recent studies on the sun-pumped laser. Currently, sun-pumped lasers are not considered due to weight and complexity penalties associated with excess heat removal and sun tracking problems.) (48:3;59:26)

The most obvious advantages of laser systems derive from their high transmission frequencies (10^{12} - 10^{14} Hz), short pulse characteristics, and narrow beamwidths. The first consequence of a high frequency is a reduction in antenna size, which leads directly to savings in weight and volume for high data rate applications. A second consequence of high frequencies is increased communication bandwidth. Some heterodyne modulation techniques offer potential bandwidths in excess of 10 GHz; unfortunately, heterodyne modulation technology has not yet approached this potential. Consequently, the Air Force relies on the short pulse width, high pulse rate capability of lasers. The high pulse rate capability has been used to demonstrate one gigabit per second communication in a quasi-operational environment, and engineers are investigating pulse modulation techniques in excess of 10 gigabits per second. (35:1-4;58:8-9;59:27)

The short pulse widths contribute to the high rate of communications, as well as to the security, or jam-resistance of laser communication systems. In the simplest sense short pulses provide jam-resistance through sheer brute force. By concentrating all the transmitted energy in a small fraction of a given interval, the effective peak power of a beam is multiplied many fold, thereby significantly enhancing the system's signal-to-noise ratio. The short pulses also permit the use of sophisticated encoding techniques. The extremely narrow and accurately timed laser pulses allow division of time into many narrow time slots, or bins, thereby permitting use of simple but highly jam-resistant encoding techniques. For high speed systems the narrow transmitter beamwidths and narrow receiver fields of view (FOV) provide the requisite jam-resistance. (29:9)

Spatial acquisition is an extremely important aspect of optical space communications due to the laser's narrow beam. Relative satellite position can be derived from ephemeride data, but fluctuations in satellite orbits cause uncertainties in the order of 10^{-3} radians in azimuth and elevation. Therefore, to acquire the target satellite it is necessary to scan the entire area of uncertainty. There are two scan and acquisition strategies/techniques currently being considered for receivers and two for transmitters. The "parallel" receiver technique simultaneously maps the entire area of uncertainty on its focal plane, where it is determined which sensor in the focal plane receives the target signal. The "sequential" receiver technique continuously analyzes the output while scanning the area of uncertainty with all sensors in the focal plane. "Parallel" transmitter technique illuminates the entire area of uncertainty at once verses "sequential" transmitter which scans the area of uncertainty with a narrow illumination beam. Acquisition using combinations of these strategies is expected to be less than 10 seconds. (52:1-5)

Laser Technology

Desirable optical communications characteristics include a small aperture (≤10 centimeters), modest weight (100-500 pounds), modest power consumption (100-200 watts), common technology and architecture for a wide range of data rates (to minimize costs and permit interoperability among future systems), easy multiplexing and switching, capability of operating with the sun in its field-of-view (FOV), an operational life greater than 7 years, and a reliable source of essential components. (11:8) Within these stated bounds, the Air Force has developed a nearterm crosslink technology goal for a system with an output power of 500 milliwatts at a wavelength of .53 micrometers, a 300 picosecond pulse width, a 500 megabit per second data transmission rate, and a 10 year life with a .95 reliability. (1:194;59:29)

The Air Force's crosslink goals have been incorporated into an optical communication system architecture. The architecture identifies two basic classes of optical receivers with salient differences centered on detection methods. One method uses a coherent source such as a heterodyne or homodyne detector. The other method is based upon an incoherent source for a direct detection system. Laser application will determine which will be used, as well as system requirements and channel effects. However, due to the more mature technology and current efforts toward becoming space qualified, an incoherent, direct detection lamp-pumped system was used as the basis for the generic laser crosslink. (See Figure 5 on next page.) (5:134C; 6:41;8:99;11:8.13-21;17:11;18:1;34:3-9;43:5.27;57:A2)

Concluding Views

The choice between MMW and laser is not easy to make, although some proponents of each view point to certain advantages. Experts working in specific areas of MMW component development point to MMW's technical and operational maturity as a distinct advantage, while other experts express concern about MMW's lack of maturity compared to systems at lower frequencies. According to

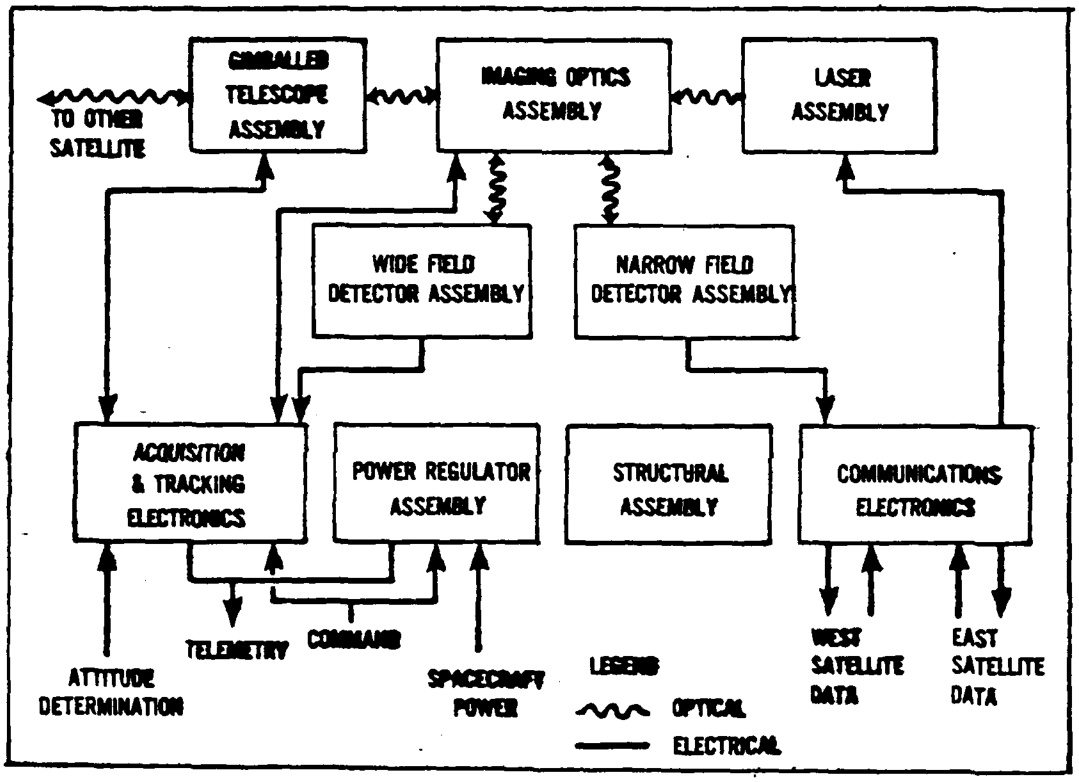

Figure 5 - Generic Laser Crosslink

Mr. D.R. McElroy (ref 42), there is no "right" solution in the choice of either "all" MMW or "all" laser for the variety of crosslink applications. Each specific application must be evaluated in detail to determine the appropriate choice. In the past, many MMW versus laser trade-off studies have been based only on data rate, weight, and power, with management's final decisions based upon available real estate and moments of inertia. Trade-off studies must include eleven key issues: data rate, weight, power, real estate/sweep volume, moments of inertia, attitude reference accuracy impact, reliability/life, ranging/timing requirement impacts, non-rigid body vibration requirement impacts, survivability, and costs. (25:1-3;42:127,128;50:59)

III. COST COMPARISON - MMW VS LASER CROSSLINK SYSTEMS

Included in Chapter III is a description of the RCA PRICE Model and the procedures used in conjunction with the PRICE Model. The RCA PRICE Model is described to acquaint the reader with the history and capabilities of the model. Following the description of the PRICE Model are discussions on the method used to collect and aggregate "expert" data, how the aggregated data was used with the PRICE Model, and the statistical significance of the output procurement costs.

The RCA PRICE Model

The PRICE (Programmed Review of Information for Costing and Evaluation) Model is a computerized method for deriving cost estimates of electro-mechanical systems. It was developed by and for Radio Corporation of America (RCA) in the early 1960s. PRICE was originally used to estimate avionics and space system costs at RCA. Interest in the model grew to the extent that arrangements were made for leasing of PRICE by analysts outside of RCA. Commercial operations began in 1975 with an average of 175 new users each year.

PRICE is applicable to all aspects of hardware acquisition including development, production, purchase, government furnished, or modification of existing equipment. PRICE estimates the costs associated with design, drafting, project management, documentation, sustained engineering, special tooling and test equipment, material, labor, and overhead. Costs for field test and site construction are not estimated by the PRICE model.

The method used in PRICE to model the estimating procedure is parametric. Therefore, when the model calculates a cost for manufacturing, it does not use a parts list and labor resource chart, but rather a parametric factor or representation of the parts and labor costs. The fundamental data used in the PRICE Model are listed below:

1. Quantities of equipment to be developed, produced, modified, purchased, furnished and/or integrated and tested.
2. Schedules for development, production, procurement, modification, integration and testing, including lead time for set-up, parts procurement, and redesign.
3. Hardware geometry consisting of size, weight of electronic and structural elements, and electronic packaging density.
4. Amount of new design required and complexity of the development engineering task.
5. Hardware structural and electronic design repeat.
6. Operational environment and specification requirements of the hardware.
7. Type and manufacturing complexity of the

structural/mechanical and electronics portions of the hardware.

8. Fabrication process to be used for production.

9. Pertinent escalation rates and mark-ups for General and Administrative charges, profit, IR&D, cost of money, and purchased item handling.

The PRICE model contains thousands of mathematical equations relating the input variables to cost. Each specific set of input parameters uniquely defines the hardware for cost modeling. The resultant cost output is determined from the mathematical equations alone (versus having the user consult additional tables or charts). Although it is always preferable for the PRICE user to supply the inputs when they are known, PRICE was designed to estimate costs with a minimal amount of hardware information. This feature makes it a legitimate tool for cost estimation of programs in the conceptual stage of development since the model uses its internally generated values for any missing input variables in order to estimate costs. Of course using known values reduces the statistical uncertainty within the parametric model.

The data files created prior to a PRICE run usually represent systems or subsystems composed of many separate subassemblies. For example, a communications satellite might be represented as a system composed of an outer structure, manuevering rockets, solar cells, and avionics. In turn, avionics might be composed of attitude reference, station keeping/satellite control, and communication subsystems. At an even lower level the communication subsystem might be composed of antenna, modulators, demodulators, digital processor, tracking circuitry, power regulator, and chassis and housing. The number of files and relative details of the parmetric information in each is determined by the PRICE user. There is no limit to the details of the data used for a PRICE analysis. Neither is there limitation that precludes a user of PRICE from treating the entire satellite as a basic assembly of the lowest order. Thus, the PRICE analysis for a satellite might be done with one data set representing the satellite as an assembly, or it might be accomplished with many files representing the satellite as a system of subsystems, assemblies, subassemblies, and so on. That decision is made by the user of the model.

Procedure

To effectively interface with the PRICE Model, it is necessary to have a basic understanding of the system to be priced. For this study the PRICE Model required an engineering design level of understanding. The voluminous details covered during the literature review was still insufficient to develop a creditable input. It was necessary therefore, to secure the aid of technical experts working with laser and MMW crosslink systems. The mode used was a questionnaire based on the PRICE Model worksheet.

Examples of the PRICE worksheets and the resulting questionnaire are found in Appendices C and D.

The expert-questionnaire approach to data gathering is basically a modified Delphi technique. The Delphi method was developed by RAND Corporation as a method to provide better technical forecasts. Although this study does not make technical forecasts per se, it did require an aggregated view of proposed advanced technology systems. The questionnaire approach is not the only way of getting the desired data, but according to Mr. Fischer (ref 28), "From a practical point of view, it makes little difference how conflicting opinions of experts are aggregated. Any reasonable approach is likely to be as good as any other."

The questionnaire was designed primarily to answer the questions addressed in the PRICE worksheet; however, additional questions were added to gain insight into current or pending technical developments that could influence the choice between lasers and MMW. Experts were asked to identify their degree of expertise - those who have had recent experience with crosslink components or systems, versus those who have worked on similar components or systems. This distinction allows the use of a weight factor in combining the answers (estimates) provided by the different experts. (The weight factor will be discussed in the next section.)

The choice of experts asked to participate was limited to authors who had contributed to laser, MMW, crosslink, and/or satellite communication studies or articles covered in the literature review portion of this study. Through this initial list further contacts were made and a total of 12 questionnaires were sent to 12 experts(4) in 10 different organizations representing private industry, government contractors, NASA, and the Air Force. Out of the 12 questionnaires sent, four were completed and returned in time to be used. The four returned questionnaires gave a good cross section of experts; those currently developing a laser crosslink or seriously looking at MMW crosslinks, or those closely following all developments in either laser or MMW crosslink arenas. (The number of questionnaires not returned, reflect the depth of expertise required to adequately answer the questions needed for input into the PRICE Model. The experts found, after receiving the questionnaire, that they either did not have the depth of knowledge or sufficient time to properly respond.)

Expertise Weight Factor. The questionnaire approach of gathering information is based upon the Delphi method. At Ref 39, several contributing authors on the Delphi method discuss ways of aggregating the opinions of the experts, including weight factors for different inputs. The conclusion expressed by all authors was that there was no prescribed method, but normally weights of 60 to 90 percent were assigned to experts closer to the problem versus those

(4) "Expert" refers to highly qualified individuals and the technical staffs which support them.

with a more casual knowledge. In the case of the crosslink questionnaire, 75% was arbitrarily used for those inputs from the experts currently developing or designing laser or MMW crosslink systems and 25% to the remaining inputs.

There was no profound reason for selecting a weight factor of 75%, just that 75% is half way between the 60 and 90% range mentioned in Ref 39. To test the sensitivity of the PRICE Model to changes in the weight factor, a test run was made on one MMW subsystem using 60% and 75%. The resultant cost comparision reflected the difference in weight factors but the difference was small compared to the difference in individual runs based upon the inputs from the experts with no weight factors being used. (See Table I below.)

Table I - Weight Factor (W.F.) Comparison on the MMW Transmitter Digital Processor Subsystem

	LOW	CENTER	HIGH
75%W.F.	1184	1334	1515
60%W.F.	1785	2013	2287
MMW Expert 1	430	479	540
MMW Expert 2	5139	5749	6499

*All costs in thousands of dollars.

<u>PRICE Model Runs</u>. Runs were made based upon data derived from each expert's questionnaire. (These runs are identified as LAS1, LAS2, MMW1, and MMW2 for laser experts 1 and 2 and millimeter wave experts 1 and 2.) This provided a means to compare differences between experts within either MMW or laser designs. The individual runs (ie., LAS1, LAS2,

MMW1, MMW2) were instrumental in highlighting those parameters which should be considered for sensitivity analysis. Following the individual runs, weighted averages of each of the PRICE input parameters were calculated for both the laser and the MMW systems. (The weighted runs are identified as LASW and MMWW.) The weighted data was then run. (See Table II).

Table II - Weighted Average and Individual PRICE Runs

	LOW	CENTER	HIGH	AVER UNIT COST
Laser.....				
LASW	50085	55676	62606	9279
LAS1	29283	32572	35893	5429
LAS2	61454	68405	77051	11401
MMW.......				
MMWW	25792	28777	32463	4796
MMW1	16382	18244	20575	3041
MMW2	59410	66456	75131	11076

*All costs in thousands of dollars.

<u>PRICE Vs Expert Estimates</u>. Along with technology estimates, the crosslink quetionnaire requested the experts to estimate the procurement cost of each subsystem. Two of the returned questionnaires provided cost estimates, one for the generic laser and one for the generic MMW systems. Since these were estimates and not "hard" cost figures, the inputs were used only as confidence checks on the PRICE outputs, not as inputs to the PRICE Model. The cost estimates for the laser came from an expert not involved presently in manufacturing of a laser crosslink though closely following all developments associated with laser crosslinks. The expert's estimates for subsystem costs were

somewhat higher than those from the PRICE Model based upon his technical input from the questionnaire. Two subsystems, beam steering and signal detection, were off by a factor of ten. When the expert was personally contacted he explained that these two subsystems could be purchased at about one tenth the price he had listed, but he felt that development of the new technology would drive the cost up by a factor of ten. From Table II the PRICE unit cost estimate was $5,429,000, whereas the expert's estimate was $8,100,000. If the system were designed with current technology, the expert's estimate would be reduced to about $6,600,000. It is interesting to note that the expert's estimate was close to the low average unit cost generated by the PRICE Model when the weighted average input data was used.

The MMW expert who provided cost estimates is currently involved in studies aimed at developing a MMW crosslink. His estimates, for the most, part were quite close to the estimates generated by the PRICE Model based on his technical inputs. The PRICE Model generated unit cost estimate was $3,041,000, while the expert's estimate was $3,975,000. As with the laser crosslink estimates, the MMW expert's estimate was close to that of the PRICE Model using the weighted average input. Table III graphically shows the comparisons for the average unit costs and low/center/high costs for six units.

Table III - PRICE Vs Expert Cost Estimates

	LOW	CENTER	HIGH	AVER UNIT
Laser.....				
Expert	*****	48600	*****	8100
LAS1	29283	32572	35893	5429
LASW	50085	55676	62606	9279
MMW......				
Expert	*****	23850	*****	3975
MMW1	16382	18244	20575	3041
MMWW	25792	28777	32463	4796

*All costs in thousands of dollars.

Statistical Analysis. With only two data points for the MMW and two for the laser, there is not much that can be done statistically. For small sample sizes t- and F-tests are commonly used. However, these statistics assume a normal distribution, an assumption hard to justify for a total sample size of four. Another statistic, the nonparametric sign test, only assumes that data points are members of continuous distributions. Thus, the sign test can be used for a wide variety of underlying distributions.

The sign test is a way of testing hypothesis about the median of a continuous distribution. The basis for the sign test is the statement, "if X denotes the random variable whose distribution is under investigation, u is the mean, and u* is the mean of a second distribution, then $P(X \leq u) = P(X \geq u) = .5$." The general null hypothesis has the form, H: u = u*. When u = 0, any X is equally likely to be positive or negative. If, however, the true value of u is much larger than zero, X is much more likely to be positive than negative, so most of the observed Xs would be positive in this case. When most sample Xs are positive, then $u > 0$ is more likely to be the case rather than $u = 0$. For testing H: $u = 0$ versus H: $u > 0$, the sign test rejects H when $Z \geq K$. The constant K is chosen so as to control the probability of a type I error (rejecting H when H is true). If the observation of each X is regarded as constituting a trial, then the experiment consists of n identical trails. If a positive X is identified with a success and a nonpositive X with a failure, then when H is true,

$$p = P(\text{success}) = P(X > 0) - P(X > u) = .5. \qquad (1)$$

When H :$u = 0$ is true, the statistic Z has a binomial distribution with parameters n, the number of tails, and $p = .5$, since the trials are independent. According to this proposition, a critical value K which ensures that P (reject H when H is true) = β, for a specified β can be found from the binomial distribution with appropriate n and $p = .5$. (22:566-568)

Looking at the cost data out of the PRICE Model, the question arises as to whether there is any significant difference between the cost data for lasers versus that of MMW. Another way of stating this would be questioning whether both sets of cost data belong to the same distribution versus being members of independent distributions/costs. (Here the null hypothesis would be, H:$u = u$.) By pairing the laser and MMW data and then applying the sign test (known in this form as the paired sign test), the probability that both sets of cost data are actually part of the same distribution can be determined. The signs of the differences between the paired observations are analyzed. If the paired observations share a common distribution, the number of positive differences and negative differences should be roughly the same. The test statistic Z is computed based upon the differences.

Using the individual laser and MMW PRICE cost data, the satistical comparsion is as follows:

$n^{(+)}$ = number of differences which are positive.

p = probability of having a difference which is positive = .5.

Binomial mean, $u = n^{(+)}p = 2 \times .5 = 1$ (2)

Binomial variance, $\sigma^2 = n^{(+)}p(1-p) = 2 \times .5 \times .5 = .5$ (3)

$Z = (n^{(+)}-u)/\sigma = 2-1/(.5)^{1/2} = 1.414$ (4)

Z(.05/2) = 1.96 (From Table A.3 Ref 22.)

Since $Z \leq Z(.05/2)$, the null hypothesis is accepted that the two distributions are equal ($u = u^*$) if 95% of all possible values of the mean are considered (95% confidence interval). At a confidence interval of 84% or less, it can be shown that Z(.16) < 1.414 and the hypothesis is rejected. Thus, at the 84% level it is possible to say that the procurement cost for the lasers is different than for MMW. This latter result (at the 84% confidence level) is supported further, as can be seen later, by the results of the sensitivity analysis where MMW costs are consistantly less than for the laser. (If a paired sign test were run on the sensitivity analysis data, the hypothesis would definitely be rejected since all differences would be of the same sign.)

Sensitivity Analysis. For the sensitivity analysis five sets of runs were made based upon changes to the weighted parametrics of the earlier runs. The first sensitivity runs were to check the effects of the possibility that the laser experts may have added subsystems which the MMW experts felt were part of the satellite, not the crosslink. Specifically, the laser power regulator, heat sink radiator, and structure were originally included in the laser parametrics but no equivalent subsystems were specifically identified for the MMW crosslink. Thus, for the first sensitivity run, the power regulator, radiator, and structure subsystems were removed. (See Table V on page 47.)

The PRICE parameters for both the laser and MMW systems were set back to the original weighted condition. For the second sensitivity run, the number of production models to be produced was raised from 5 to 120, and the date by which the last system was to be manufactured was extended from December 1988 to Dec 1996. The increase of production units allows for economics associated with large system buys to have an effect. The third set of runs was to complement the second set by extending the end of the production date from 1996 to 2006. (See Tables VI and VII on page 47.)

From earlier runs based upon the individual experts' inputs, it was seen that there was one cost factor which seemed to cause the laser crosslink to have higher costs than the MMW. This factor was the percent of new electronic design. Laser subsystems consistantly had a higher percent of new design. Using the original parametric model, new electronic design was changed to 30.7% for all laser subsystems. The 30.7% is the overall percentage of new electronic design for the MMW crosslink system. With these changes, runs were made and costs compared to the original weighted MMW cost data. (See Table VIII on page 47.)

The final sensitivity run was designed to determine the effects due to differences in weight of the two systems. The weighted average laser crosslink weight was 516.7 pounds while the weighted average MMW crosslink was 300.5 pounds. To make the laser system the same weight, all components were multiplied by a factor of .5819132 (300.5/516.7 = .5819132). With these changes, runs were made and the output compared to the original weighted MMW cost data. (See Table IX on page 47.)

Reflected in these tables are some points of interest. Between Tables IV and V, the cost difference between the laser and MMW crosslink systems were reduced by 33.4%. The only change made to the input data for Sensitivity Run 1 was to eliminate the laser power regulator, radiator, and structure. This comparision is an indication of the magnitude of change due to uncertainty which can result when designers make different assumptions of what is and what is not included.

In Run 2 (Table VI) there is a significant decrease in unit cost of both the laser and MMW systems. The major factors in the decreased procurement costs are: the initial R&D cost is spread over a larger buy, learning curve improves production efficiencies, and component manufacturing technology is assumed to be more mature.

Weight is one of the parameters used by the PRICE Model to generate a cost estimate. In Run 5 the weight of the laser crosslink was scaled down to be equal to the total weight of the MMW system. As can be seen in Table IX, the reduced weight caused a 28.8% decrease in average unit costs. Thus, system/subsystem/component weight can be considered an important input parameter to the PRICE Model.

A final point on the sensitivity runs concerns Run 4. Setting the percent of new design for lasers equal to the average value for MMW, allows a look at what may happen to procurement costs as laser technology gains in maturity. In Run 4 the effect is a 25.8% decrease.

Table IV - Original Weighted Runs

	LOW	CENTER	HIGH	AVER UNIT COST
LASW	50085	55676	62606	9279
MMW	25792	28777	32463	4796

Table V - Run 1 (Laser System Less Power Regulator, Radiator, and Structure)

	LOW	CENTER	HIGH	AVER UNIT COST
LASW	42038	46697	52399	7783
MMW	25792	28777	32463	4796

Table VI - Run 2 (Original Parameters Except Production Increased to 120 vs 5 Units and End of Production Date Set at Dec 1996)

	LOW	CENTER	HIGH	AVER UNIT COST
LASW	201796	234080	271009	1935
MMW	123354	143719	167206	1188

Table VII - Run 3 (Same as Run 2 Except End of Production in 2006)

	LOW	CENTER	HIGH	AVER UNIT COST
LASW	240762	279182	322945	2307
MMW	147092	171141	198789	1414

Table VIII - Run 4 (Original Weighted Parameters Except All Laser New Electronic Design Set at 30.7%)

	LOW	CENTER	HIGH	AVER UNIT COST
LASW	37018	41332	46579	6889
MMW	25792	28777	32463	4796

Table IX - Run 5 (Original Weighted Parameters Except LASW Total Weight = MMW Total Weight)

	LOW	CENTER	HIGH	AVER UNIT COST
LASW	35770	39667	44522	6611
MMW	25792	28777	32463	4796

*All costs in thousands of dollars.

IV. CONCLUSIONS and RECOMMENDATIONS

This final chapter presents a summary of the findings from Chapters II and III. Based upon these findings, recommendations are presented for topics of further study and Air Force action.

Conclusions

Literature Review. From review of the literature there is a strongly implied requirement for satellite crosslink networks to support the military's worldwide command and control. The requirement is for a network which is highly interference and ECM resistant, and compact enough not to interfere with other systems on a host satellite. These requirements have been instrumental in the push towards the shorter wavelengths associated with millimeter wave and laser satellite communications. Also drawn from current writings is support for the assumption that both MMW and lasers can satisfy the crosslink requirements, although off-the-shelf, space qualified components are not available for all subsystems. Another important point discussed in the literature review portion of this study was the fact that in considering laser versus MMW, it is necessary to evaluate 11 separate factors to adequately make a complete trade-off analysis.

PRICE Runs. Through the use of the RCA PRICE Model, the procurement costs of generic laser and MMW crosslinks were developed and compared. The PRICE Model also allowed variations to the experts' inputs to determine the sensitivity of the model to changes in weight, percent of new design, quantity produced, length of production run, and changes in system make-up. From these runs it was seen that MMW consistantly had lower procurement costs.

Sensitivity Runs. From the sensitivity analysis it was seen that uncertainty of design was a major factor leading to increased procurement costs. Evidence of this could be seen in the large decrease in cost when percent of new electronic design for the laser system was reduced. This affect of design uncertainty was also reflected in the difference in procurement costs of sensitivity analysis Run 1. In Run 1 the point was made that if the MMW design had not actually included systems equivalent to the laser's power regulators, radiators, and structures, then MMW cost figures would have a built-in cost advantage. Seeing how the cost of the laser system significantly decreased as percent of new design decreased, it can be expected as laser crosslink technology gains in maturity the degree of uncertainity in design will become comparable to MMW. At that point the difference in MMW and laser procurement costs will probably become insignificant. This point is further supported in sensitivity analysis Run 2. In Run 2, large scale production (121 units) brought the difference in laser and MMW unit procurement costs to $747,000 versus $4,483,000 under the original condition of a buy of six units.

Confidence Factors. In considering the procurement cost figures, there are many factors associated with the PRICE input parameters which could greatly alter the outcomes. First, as part of the cost analysis, certain technologies were locked-in by defining the generic crosslink systems; technology had to be defined and constrained to a region where both MMW and laser systems could be equally effective. However, it is known that optical crosslinks gain a significant weight advantage at data rates above 10 Mbps. Since weight is a key cost factor in the PRICE Model, a design requirement of 100 or 1000 bits per second would improve laser procurement costs versus that of MMW. Another factor which could alter the outcome of the PRICE runs can be attributed to the method of defining the generic laser and MMW systems. The Delphi technique along with the weight factor is obviously not totally accurate in predicting the design of a hypothetical system. As a result, the technology, designs, and associated cost factors are accurate only to an order of magnitude at best, and it has already been shown that estimates of weight and percent new design can greatly alter the cost outcome.

Sample size is another factor to be considered in understanding the results of the PRICE Model runs in this study. A relatively small sample size carries with it a large degree of uncertainty. It was shown statistically with such a small sample size and a large variance within the sample, there was a chance (at the 85% confidence level or greater) that the cost outputs for lasers and MMW could have been part of the same distribution - meaning there would be no statistical difference in the procurement costs between laser and MMW crosslinks. The most important point to be surmised from the statistical analysis is that the cost figures are not exact. Therefore, the cost differences derived from the PRICE Model runs for laser and MMW, can not be considered exact.

Study Results

So what can really be said about the outcome of the PRICE Model runs in this study? What can be said is MMW consistantly came out having lower procurement costs. This reflects the fact that today MMW has the more mature technology for satellite crosslink communications. If this is in fact the major difference in procurement cost, then after the completion of McDonnell Douglas' laser crosslink development program, the two technologies should approximate each other in maturity which should eliminate much of the differences in procurement costs. As the costs of laser and MMW crosslinks become closer in magnitude, the significance of procurement cost as a trade-off factor becomes less; this in turn places greater importance on the technology and operational issues.

Trade-off Studies. As stated in Chapter II, there is no right solution in the choice of either proceding with all laser or all MMW. Each specific application must be evaluated in detail to determine the appropriate choice. Trade-off studies must consider eleven design and cost factors: data rate, weight, power, real estate/sweep volume, moments of inertia, attitude reference accuracy impact, reliability/on-orbit life, ranging/timing requirement impacts, non-rigid body vibration requirement impacts, survivability, and costs.

The PRICE Model. Through this study confidence in the PRICE Model was gained. For this study the PRICE Model cost estimates were within a reasonable range of the estimates provided by the experts. Also, the PRICE output was broken down into R&D and procurement costs which give the analyst quantified areas for comparison and further study. For the PRICE Model to work effectively requires the analyst and design engineer to sit down and understand the capability and limitations associated with the systems involved. Such a close involvement gives the analyst and design engineer a better feel for what are the "cost drivers" and the sensitivity to changes in parametric inputs. As a result, working together provides better (closer to reality) estimates.

Recommendations

(1) As brought out in the literature review, cost

analysis by itself does not make a complete trade-off study. Recommend that a complete trade-off study be made using the eleven factors as identified in Ref 42. Further, recommend as part of the trade-off study that multiple data rates be used, say from 100 kbps to 1 Gbps. Varying the data rates would provide results which would fit requirements of a variety of crosslink uses (ie., for crosslinks which pass satellite control commands, military teletype channels, and high speed computer-to-computer data.)

(2) A limiting factor in the development of either a MMW or laser crosslink system could be lack of dedicated funding. This problem can be reduced if the military users have validated requirements which support the necessary level of funding. Today, a few key people have pushed for employment of crosslinks in military communication satellites; however, there are no validated requirements that specifically support the need for crosslinks. Without validated requirements to drive the programs, the funding will never be adequate. The people responsible for developing communication counter-counter measures and survivability for the military's C^3I, and those responsible for ensuring that this country's Rapid Deployment Force has the necessary communications wherever they may be sent, are some of the people who should be working closely with Air Force Systems Command/Space Division and Air Force Communications Command to get the necessary requiremen ⌄ stated and validated.

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APPENDIX A

CURRENT MILLIMETER WAVE TECHNOLOGY

The generic MMW crosslink described in Chapter II depends heavily upon solid state technology for high reliability, low power consumption, and light weight. In the transmitter and receiver portions of the system, solid state amplifiers and oscillators provide the output carrier frequency and power needed to allow the crosslink to operate over several thousand miles between satellites. (20:4-19;29:65,67;34:5-22,28)

The two leading contenders as oscillators and power amplifiers are IMPATT and GUNN diodes. Diodes are rated on their noise figure, power out, and efficiency. The power obtainable from IMPATT devices is greater than available from GUNN devices, but at the expense of higher noise figures (10-15 dB more noise degradation) and greater operating voltages. Current IMPATT performance specifications achieved are noise figures of 33-35 dB, 4 watts output power, and 6% efficiency. Most of the improvement in IMPATTs has been the development of the double-drift silicon diode with diamond heat sink. The double-drift diode provides a more efficient removal of the heat dissipated in the active portion of the devices. Heat removal has been the limiting factor in the IMPATT reliability performance. In order to get an operating life greater than 10^4 hours, manufacturers have specified a maximum junction temperature of 250 degrees. Significant improvement is expected as IMPATT technology goes into Gallium Arsenide (GaAs) with its higher mobility and lower series resistance. With GaAs the IMPATTs should see a 10 dB improvement in the noise figure. (This would still preclude their use in receivers.) A GaAs IMPATT diode is being developed for a 60 GHz amplifier as a possible backup for a laser communication crosslink system proposed for DSCS-IV satellite. Additional improvement is expected in active tuning elements (such as varactors) integrated into the diodes to achieve broad voltage tuning ranges. Currently devices have 5 GHz mechanical and .1 GHz voltage tuning ranges. (1:41,72;27:2,3;34:2-3,5,7,16;56:6)

GUNN diode oscillators have been available for the last 15 years, and span the radio frequencies from India band to 100 GHz. A characteristic of GUNN amplifiers is their noise level does not appreciably vary from 20-100 GHz (18 dB at 20 GHz and 22 dB at 100 GHz). Typical continuous-wave power out is 30 milliwatts and 10% efficiency for a GUNN diode operating at 94 GHz. Major improvement for GUNN diodes is expected with the successful development of an Indium Phoshid (InP) diode. The InP GUNN diode would give 3 dB improvement in power out and 4 dB improvement in noise. (34:2-3,13,16)

Closely associated with oscillators and power amplifiers are frequency multipliers. Many variations of the basic multiplier have been built and flown aboard satellites. Multipliers are mainly used for frequencies over 100 GHz and as low power, broadband sources for phase-lock applications under 100 GHz. Current work on frequency multipliers has been with silicon (Si) and GaAs varactors to achieve efficient multiplier stages. A single diode doubler stage with a 15 GHz input at .5 watt gives 30 GHz with 35% efficiency. Cascaded chains have provided an output of 94 GHz at 10% efficiency, 1 GHz bandwidth, and an output power of 50 milliwatts. (34:2-7,8)

In MMW receivers down converters/mixers are used to convert the exceptionally high frequencies of the received signal to microwave frequencies at the preamplifier. Most mixers use silicon Schottky barrier diodes mounted in a folded hybrid tee. These devices are responsive over bandwidths from .1 to 2 GHz. MMW mixer preamplifiers such as these have already been operationally tested in satellite systems. Long-term improvements are expected to provide decreased conversion loss (to within 4 dB of theoretical) and full waveguide bandwidth. The technology leading the way to the expected improvements is the superconducting Schottky mixer which uses a superconducting metal contacted to a heavily doped semiconductor and requires cryogenic cooling. (34:2-24,26)

In the receiver front end are the radio frequency (RF) detectors. The majority of the MMW detectors use silicon Schottky barrier diodes mounted directly into the waveguide.

There are two basic packaging schemes: below 50 GHz miniature sealed glass package and above 50 GHz unsealed package mounted in an improved sharpless-type wafer. Both packages are rugged enough for space applications. Long-range development in MMW detectors will center around zero-bias GaAs Schottky barrier diodes. These will provide simple and stable detector circuits presently available only at lower microwave frequencies. (34:2-32)

Not all satellite communications hopes are invested in solid state components. Development efforts continue on power amplifier tubes. The greatest advantage of tubes over solid state devices, such as IMPATT amplifiers, is the higher output power. Although commercially available tubes are rated at 1-10 watts with up to 10% efficiency, tubes such as the gyrotron are theoretically capable of producing output power levels measured in millions of watts. (10:54) For space applications the prime design factors are life and efficiency. Cathodes are the prime limiting component in tube life. Using dispenser or impregnated cathodes is expected to achieve lifetimes in excess of five years. The Japanese CS communication satellite used a helix traveling wave tube (TWT) for its EHF up- and downlinks. The helix produces an RF of about 20 GHz, with a 1 GHz bandwidth, using 21 watts of power to produce 4 watts of output power. Also, feasibility models have been developed using coupled cavity TWTs. These models are expected to result in tubes producing 100 watts of output power at 24% efficiency and have a 1.2% bandwidth at an output RF of 20-40 GHz. (34:3.12-17)

Antenna design is an important factor in the overall design of a satellite. Horn, cassegrain, offset feed reflectors and lens have been used or will be used in spaceborne MMW antenna designs. To provide the required gain a large gain antenna is needed. In a space environment, use of large gain MMW antenna will impose additional problems of thermal stability, high rigidity, and tight tolerances, and at the same time maintain a light structure. To help overcome these structure/tolerance problems, composite materials are being developed for future spacecraft uses. (29:88;34:5-23;56:5)

Another consideration in antenna and spacecraft design is the effects of mechanically scanning the antenna or antenna feed. In accordance with Newton's law that for every action there is an opposite but equal reaction, movements at the antenna must be offset elsewhere on the satellite to maintain its stability. One way of overcoming this complex problem is to use electronically scanned array antennas. Space capable phased and lens array antennas have been under development since 1979 and should reach operational status within the next 10 years. (29:88;34:5-22,23)

Tying antenna and electronic components together are waveguides. Both rectangular and circular waveguides and cavities are commonly used at MMW frequencies. Due to the appreciable losses at these frequencies, a circular waveguide is used for long runs and outweighs the additional complexities of mode suppression techniques required with circular waveguides. In general, the waveguide insertion loss is inversely proportional to the wall circumference; the larger the waveguide the lower the loss. The increased size, however, lowers the cutoff frequency and permits other modes to propagate in the guide. Critical constraints are placed upon the path configuration to minimize transmission line loss and extraneous modes. The tight tolerances demanded by these constraints has led to the development of graphite-epoxy composite materials. Waveguides made of this material weigh one-third that of typical aluminium waveguides, and have an order of magnitude less thermal expansion. Beyond conventional waveguides, technological developments show promise in the areas of coplanar waveguides, slotline, fin line, image line, microstrip, and suspended stripline. Low loss propagation at MMW, sub-millimeter wave, and even optical frequencies is theoretically possible by using refractive dielectric guides and image guides, but such devices are not expected in the nearterm. (34:4.1-10)

APPENDIX B - CURRENT LASER TECHNOLOGY

For an incoherent source the received optical energy is detected via a photodetector for signal gain (eg., photomultiplier tube (PMT) or avalanche photo-detector (APD)). Front end gain is required because of the low signal power received (typically about 100 photons/information bite). The front end of a coherent receiver acts as a linear amplifier and converts the received optical field into an electrical output; thus it does not require an additional amplifier at the detector. (11:8.13-21;35:1-4)

Presently, incoherent systems possess the more mature technology. However, the push is towards coherent systems since they require 10-13 dB less transmission power than do incoherent systems. Other advantages of incoherent systems are the receiver optics do not have to be diffraction limited, spatial tracking is simple (ideal for wide FOV applications), and requirements are minimal on laser temporal spectral purity (frequency tracing is unnecessary). Disadvantages are high peak power is necessary for background noise discrimination (this tends to shorten laser life), communications performance can be background noise limited especialy with the sun in the FOV,

and demodulation into a bitstream at the receiver is required. (Although noise limited, improved performance can be achieved by use of coding on digital signals.) Conversely, the coherent laser can operate with the sun in its FOV, is easily multiplexed, has longer lifetime, and is capable of interoperability for systems with different data rates. To reap these gains it is necessary to have a stable, single frequency laser and requires frequency acquisition and tracking.
(5:134C;6:41;8:99;11:8.13-21;17:11;18:1;43:5.27;51:428)

Currently, the only space qualifiable lasers are the doubled/mode-locked and Q-switched Nd:YAG lasers. However, to be viable as part of space-based systems, each laser must have a reliable and efficient pump. Lamp-pumped lasers are often used with crystalline lasers, but lamp lives are only a few thousand hours. Another drawback of a lamp pump is their output power conversion efficiency is typically less than 1%. Under development is a laser pump made up of 100 laser GaAlAs diodes in stacked arrays. These 100 diodes working together have a longer lifetime and provide overall efficiencies of about 1%. (11:8-21;17:1;38:2;47:23,30;57:A2)

Crystalline lasers (ie., Nd:YAG) and semiconductor lasers (ie., GaAlAs) have great potential as coherent sources for space communication systems. GaAlAs lasers are much more efficient (about 10%) than crystal lasers. The upper limit on output power for a semiconductor is about 200 milliwatts; tests indicate by using a heterodyne system, a few hundred milliwatts at one micrometer is adequate for a 1 gigabit per second system. If more receiver power is needed, optics aperture can be increased. (11:8-22,23;16:1)

A high data rate communications system under consideration employes a satellite control receiver (at 21 kilobits per second), a 1 gigabit per second receiver, a wide-area, multiple-access receiver, and a low data rate transmitter. The high data transmitter has a 5 microradian (urad) beamwidth through a 20 centimeter optical telescope. At synchronous orbit the 5 urad would project a .1 mile diameter spot onto the earth. The high data receiver has a 62 centimeter telescope, high speed detectors, and receiver electronics to resolve the time delay and polarization of the incoming data stream. The FOV of the receive optics is 100 urad. The control transmitter serves as a beacon laser for a closed-loop acquisition and track system. This beacon uses pulse interval modulation to discriminate between noise photoelectrons (ie., jamming, background noise, and internal noise) and authorized data streams. The control receiver is built into the high data rate transmitter. Fine pointing is provided by a torque motor which adjusts beam steering mirrors mounted at critical locations in the optical path. This high data rate system weighs 550 pounds and requires about 550 watts. (48:5)

In general the use of laser crosslinks requires design and development of extremely high precision tracking and pointing control systems due to the narrow beamwidths.

Microradian point/track is required, as is submicroradian beamjitter stability. Due to the great range separation between two geosynchronous satellites, "look ahead" compensation may be necessary. Initial acquisition and re-acquisition depends heavily on satellite attitude control, and determination of the satellite's uncertainty volume. Seven to ten year operational life imposes stringent requirements on tracking and control loop designs. Another requirement which must be met before space-based laser communications will be practical is the development of techniques to interface optics with high speed electronics. (1:194,204)

APPENDIX C - PRICE MODEL WORKSHEETS

Within this appendix are two different PRICE worksheets. The "Hardware Parametric Data Sheet" was used as the outline for the crosslink questionnaires. Based on the guidance provided by an Air Force Systems Command/Aeronautical Systems Division (ASD) PRICE analyst, only those sections which pertain to space communications systems were included in the questionnaire.

The input to the PRICE Model was generated by data contained on the "PRICE Input Data Worksheets." For each run there was a Input Data Worksheet for each subsystem. The information on these worksheets came from a the questionnaires, the RCA PRICE 84 - H Reference Manual, and recommendations of the ASD PRICE analyst based upon her prior experience with Air Force electronic systems. The sample worksheet has been divided into rows I - VI and columes A - E. An explanation of the parameters follows:

I.A. Production Quantity. Five crosslink systems were specified corresponding to requiring four systems to be operational and having one spare. The number of systems produced was increased to 120 for Sensitivity Runs 2 and 3.

I.B. Prototypes. One prototype was specified. The prototype would be used for either configuration management or as a research and development platform for testing configurations and interfaces.

I.C. Weight. The weight varied for every subsystem on every run. The weight was based on data contained in the crosslink questionnaire, question #2.

I.D. Volume. Same as I.C. above except that data was based on question #1.

I.E. Mode. Mode "1" was specified which corresponds to analysis of electro-mechanical systems.

II.A. Quantity. Quantity relates to the number of subsystems per satellite. The actual number used was based on data contained in the crosslink questionnaire, question #4.

II.B. Electronic Integration Factor. The values specified varied from subsystem to subsystem. The value used in each case was abstracted from the PRICE Reference Manual, Table A INTEGE.

II.C. New Structure Integration Factor. Same as for item II.B.

II.D. Specification Level. A value of "2" was specified, corresponding to analysis of unmanned space systems.

II.E. Year of Economics. 1983 was used for all runs.

III.A. Structure Weight. Based on data contained in crosslink questionnaire, question #3.

III.B. Manufacturing Complexity. Data varied from subsystem to subsystem. The value used was derived from the

PRICE Reference Manual, Table B MCPLXE.

III.B. New Structure. A value of "1" was specified corresponding to 100% new structure. The structure of each subsystem would be tailor made to meet the physical restrictions of the satellite and other systems to be integrated into the satellite.

III.C. Design Repeat. The percent of design which could be derived from other satellite systems was unknown, therefore the ASD analyst recommended the use of "C" (which corresponded to the RCA default value of about 25%).

IV.A. Electronic Weight/ft^3. The electronic density varied from system to system depending upon amount and type of integrated circuits employed. Actual values used were derived from the crosslink questionnaire, question #10 and PRICE Reference Manual, Table C MCPLXS.

IV.B. Manufacturing Complexity. Same as item IV.A. above.

IV.C. New Electronics. Value used based on data contained in crosslink questionnaire, question #5.

IV.D. Design Repeat. Same as item III.D. above.

V.A. Development Start. 1283 (Dec 1983) specified - analyst's choice.

V.B. Prototype Complete. ASD analyst recommended 1286 (Dec 1986).

V.C. Development Complete. 1286 (Dec 1986) was selected to coincide with the prototype completion date.

V.D. Engineering Complexity. ASD analyst recommended a value of "1.9" be used, corresponding to the manufacturer having experience making similar space systems but no experience in making the specific crosslink system under study.

VI.A. Production Start. The prescribed production start date was selected so as to immediately follow the prototype finish date - "187" (Jan 1987) was used.

VI.B. First Article Delivery. ASD analyst recommended a production rate of one crosslink system every six months. "787" (Jul 1987) was used.

VI.C. Production Complete. "1288" (Dec 1988) was used based on a production rate of one every six months and a total of five systems produced. This value was changed to "1296" (Dec 1996) and "1206" (Dec 2006) for Sensitivity Runs 2 and 3, respectively.

VI.D. Cost-Process Factor. ASD analyst recommended ".9", corresponding to production methods employing both manual and automatic assembly techniques.

HARDWARE PARAMETRIC DATA SHEET

(Use Additional Pages as Necessary)

HEAVILY LINED AREAS DESIRED BUT NOT MANDATORY

1. NAME OF UNIT

2. NAME OF CONTRACTOR

3. WORK BREAKDOWN STRUCTURE ELEMENT NO. (NOS)

4a. CONTRACT LINE ITEM NO. ____________

4b. REFERENCE TECH VOL. ____________

5a. QTY OF THIS UNIT USED IN NEXT HIGHER ASSY

5b. NAME OF NEXT HIGHER ASSY

6. NAME OF SYSTEM OR SUBSYSTEM

7. MILITARY SPECIFICATION REQUIRED
- ☐ YES, SPEC. NO. __________ (IF KNOWN)
- ☐ NO. (EXPLAIN IN REMARKS)
- ☐ UNKNOWN

8. SPECIAL ENVIRONMENTAL REQUIREMENTS
- ☐ RADIATION HARDENING ☐ TEMPEST
- ☐ OTHER (EXPLAIN IN REMARKS)

9a. SOURCE OF UNIT
- ☐ MANUFACTURED (IN-HOUSE)
- ☐ PURCHASED (SEE NO. 10)
  - ☐ OFF THE SHELF
  - ☐ CUSTOM MADE
- ☐ GFE

9b. IF PURCHASED OR GFE, ENTER % MODIFICATION REQUIRED
- ______ % OF TOTAL, ELECTRONIC
- ______ % OF TOTAL, MECHANICAL

(EXPLAIN MODIFICATIONS IN REMARKS)

10. IF PURCHASED

SUPPLIER NAME ____________

PROTOS. UNIT COST $ __________ ☐ FIXED ☐ TO BE ESCALATED

PROD. UNIT COST $ __________ YEAR $ __________

IF ESCALATED, INDICATE SCHEDULE AND RATES

PHASE (SEE 28)	SCHEDULE FROM	TO	RATE	OR GOV'T STD
____	____	____	____ %	☐
____	____	____	____ %	☐
____	____	____	____ %	☐
____	____	____	____ %	☐
____	____	____	____ %	☐

11a. PHYSICAL DESCRIPTION (REFERENCE TECHNICAL VOLUME. INCLUDE PHOTOGRAPHS OR EXPLODED VIEWS OR SCHEMATICS, AS APPROPRIATE.)

11b. FUNCTIONAL DESCRIPTION (DESCRIBE FULLY. INCLUDE WHERE AND HOW USED AND CHECK CATEGORY IN 19 WHICH MOST CLOSELY FITS – INDICATE TYPE OF DISPLAY OR READOUT.)

12a. ENCLOSURE CONSTRUCTION

ENCLOSURE MATERIAL AND THICKNESS (INCHES) __________

SPECIAL PROCESSES (CHECK ANY THAT APPLY)

- ☐ MACHINING
  - ☐ MODERATE
  - ☐ CONSIDERABLE
- ☐ MILLING
- ☐ BRAZING
- ☐ POLISHING
- ☐ SHOCK MOUNTING
- ☐ WELDING
- ☐ CASTING
- ☐ X-RAY INSPECTION

12b. DISCRETE STRUCTURAL/MECHANICAL MODULES (e.g., GYROS, MOTORS, FANS, TRANSFORMERS, ENCLOSURE, BATTERIES, ANTENNAS, CABLING, TWT, ETC.)

NAME OF MODULE	VOLUME (FT³)	WEIGHT (LBS)	QTY/ASSY	SOURCE: MADE	% NEW DESIGN	PURCH	COST ($)	YEAR
____	____	____	____	☐	____	☐	____	____
____	____	____	____	☐	____	☐	____	____
____	____	____	____	☐	____	☐	____	____

13a. NAMES OF OTHER UNITS INTERFACING WITH THIS UNIT

13b. CHECK THE APPROPRIATE BOXES BELOW TO INDICATE INTEGRATION REQUIREMENTS

MECHANICAL INTEGRATION
- ☐ ONE SURFACE MOUNTING, NO MACHINING.
- ☐ TWO SURFACE MOUNTING, NO MACHINING.
- ☒ MODERATE MACHINING, SHIMMING.
- ☐ CONSIDERABLE MACHINING.

ELECTRONIC INTEGRATION
- ☐ POWER FURNISHED TO ASSEMBLY.
- ☐ POWER FURNISHED, CABLED OUTPUT.
- ☐ AS ABOVE, PLUS CALIBRATION, ADJUSTMENT, TUNING.
- ☐ AS ABOVE, PLUS PARTS AND/OR SUB-ASSY REPLACEMENT.

14. OTHER APPLICATIONS OF THIS UNIT (INDICATE IF DESIGN, OR % OF DESIGN, FUNDED UNDER OTHER PROGRAMS. IF SO, SHOW AMOUNT FUNDED. DOES PREVIOUS DESIGN REQUIRE MODIFICATION? ______. WHAT % REQUIRES MODIFICATION? ____. IF PRODUCED IN OTHER PROGRAM, SHOW QUANTITY, PRODUCTION SCHEDULE, AND UNIT OR TOTAL PRODUCTION COST.)

15. UNIT GEOMETRY AND WEIGHT

TOTAL UNIT WEIGHT (LBS) __________

UNIT VOLUME (FT³) __________

– OR –

UNIT DIMENSIONS __________

(ATTACH DIAGRAM)

16. METHOD OF COOLING (e.g., BLOWERS, HEAT SINKS, PIPING, ETC.) INCLUDE WT. IN 12b and 17.

17. TOTAL STRUCTURAL/MECHANICAL WT (LBS) (INCLUDE WEIGHT OF ALL BUT ACTIVE ELECTRONICS)

18. ESTIMATED TOTAL % NEW DESIGN OF ALL STRUCTURAL/MECHANICAL COMPONENTS

19. TYPE OF ELECTRONICS (SEE NO. 20)

- ☐ ANALOG
  RECEIVERS OR AMPS, AUDIO VIDEO, RF, SERVO DRIVE, ETC.
- ☐ TRANSMITTER
  TV, RADAR, COMM, NAV, LASER, ETC.
- ☐ DIGITAL
  GATES, REGISTERS, COMPUTERS, ETC.
- ☐ POWER SUPPLY
  - ☐ CONVENTIONAL LINEAR RECTIFICATION
  - ☐ CHOPPER & AC–DC CONVERTERS
- ☐ DISPLAY WITH CRT (INCLUDES CONTROL CIRCUITS)
  TV VIEWERS, RADAR SCOPES, OSCILLOSCOPES, ETC
- ☐ DISPLAY – NO CRT (INCLUDES CONTROL CIRCUITS)
  LED's, LIQUID CRYSTAL, PRINTERS, ETC

20a. ELECTRONIC DESCRIPTION BY PERCENTAGE OF CONTENT

TYPE (AS IN 19)	% DISC.	% SSI/MSI	% LSI	% VLSI	% HYB.	% VHSIC	PKG. (DIP LCC, ETC)
ANALOG							
DIGITAL							
DISP. W/CRT							
DISPLAY							
XMTR							
PWR. SUP							
% CATALOG							
% CUSTOM (SEE 21)							

20.b. P.C. BOARD DATA (FINISHED ASS'Y WITH 20.a COMPONENTS)

TOTAL NO. OF BOARDS ______ AVG. BOARD SIZE (IN) ______

AVG. NO. LAYERS ______ AVG. BOARD WEIGHT ______

UNIQUE TYPES – NEW ______ OLD ______ MOD. ______

20.c. OTHER ELECTRONIC MODULES/ASSEMBLIES (R.F., P.S., ETC)

NAME OF MODULE	VOLUME (FT³)	WT (LBS)	QTY	MFD (IN-HSE)	% NEW DESIGN	PURCH ITEM	COST ($)	YR ($)
				☐		☐		
				☐		☐		
				☐		☐		

21.a. NEW OR CUSTOM MICROCIRCUIT CHIPS (FROM 20.a)

CHIP TYPE	REQ'D QUANTITIES PROD.	LOT PROTOS	SIZE IN MILS LENGTH	WIDTH	NO. OF PINS I/O	NO. OF GATES OR XSTRS.	% NEW CELLS	% CELL REPEAT	DES./PROTO ITERATIONS	(IF PURCH'D) COST - $

21.b. OTHER CHIP DATA

SPEC. SOURCE* ______

DESIGN SOURCE ______

MFG. SOURCE ______

TYPE OF PKG. ______

*COMMERCIAL, MIL SPEC. OR SPACE ORIENTED FACILITY

22.a. SCOPE OF DESIGN EFFORT

- ☐ SIMPLE MODIFICATION TO AN EXISTING DESIGN
- ☐ NEW DESIGN, DIFFERENT FROM ESTABLISHED PRODUCT LINE, USES EXISTING MATERIALS AND/OR ELECTRONIC COMPONENTS.
- ☐ EXTENSIVE MODIFICATION TO AN EXISTING DESIGN
- ☐ NEW DESIGN, DIFFERENT FROM ESTABLISHED PRODUCT LINE, REQUIRES IN-HOUSE DEVELOPMENT OF NEW ELECTRONIC COMPONENTS, OR NEW MATERIALS AND PROCESSES.
- ☐ NEW DESIGN, WITHIN ESTABLISHED PRODUCT LINE, CONTINUATION OF EXISTING STATE OF ART.
- ☐ STATE OF ART BEING ADVANCED, OR MULTIPLE DESIGN PATH REQUIRED TO REACH GOALS.

22.b. EXPERIENCE OF DESIGN TEAM

- ☐ EXTENSIVE EXPERIENCE WITH SIMILAR TYPE DESIGNS, MANY EXPERTS IN FIELD, TOP TALENT LEADING EFFORT.
- ☐ NORMAL EXPERIENCE, ENGINEERS PREVIOUSLY COMPLETED SIMILAR TYPE DESIGNS.
- ☐ MIXED EXPERIENCE, SOME ARE FAMILIAR WITH THIS TYPE OF DESIGN, OTHERS ARE NEW TO JOB.
- ☐ UNFAMILIAR WITH DESIGN, MANY NEW TO JOB.

23. UNIT QUANTITIES AND SCHEDULES (1 - INCLUDE FOLLOW-ON PRODUCTION IF APPLICABLE, 2 - DESCRIBE YIELD PROBLEMS IN REMARKS)

PHASE (AS APPLICABLE AND/OR AS DEFINED IN RFP) [1]	— QUANTITIES TO BE PRODUCED — IN ENGINEERING SHOP (INCLUDE NON-DELIVERABLES) [2]	IN PRODUCTION FACILITY (INCLUDE NON-DELIVERABLES) [2]	UNIT START DATE	FIRST ARTICLE COMPLETE	LAST ARTICLE COMPLETE	PHASE END DATE (AS APPLICABLE)
I						
II						
III						
IV						
V						

24.a. DESCRIBE PRODUCTION PROCESSES (AUTOMATED-SKILLED LABOR, ETC.)

MECHANICAL

ELECTRONICS

24.b. DEGREE OF AUTOMATION

	MECHANICAL	ELECTRONICS
MAXIMUM	☐	☐
NORMAL	☐	☐
MINIMUM	☐	☐

24.c. INDICATE LEARNING CURVE – INDUSTRIAL (MATERIAL, LABOR, AND TYPE OF L/C)

25. REMARKS (ATTACH ADDITIONAL PAGES AS NECESSARY.)

26a. NAME & PHONE NO. OF PREPARER

26b. NAME & PHONE NO. OF AUTHORIZED CONTACT

PRICE Input Data Worksheet

Basic Modes

File name:
Sheet ___ of _____

**PRICE 84 (This must be used only as the first line of the file.)

Title: A B C D E **Date:**

General A I	Production Quantity QTY	Prototypes PROTOS	Weight (lbs) WT	Volume (ft³) VOL	MODE	1 E/M ITEM 2 MECHANICAL ITEM 6 MODIFIED ITEM 7 ECIRP 10 DESIGN TO COST
General B II	Quantity/Next Higher Assembly QTYNHA	NHA Integration Factors Electronic INTEGE	Structural INTEGS	Specification Level PLTFM	Year of Economics YRECON	Year of Technology YRTECH
Mechanical/ Structural III	Structure Weight WS	Manufacturing Complexity MCPLXS	New Structure NEWST	Design Repeat DESRPS	Equipment Classification MECID	Mechanical Reliability MREL
Electronics IV	Electronics Weight/ft³ WECF	Manufacturing Complexity MCPLXE	New Electronics NEWEL	Design Repeat DESRPE	Equipment Classification CMPID	Electronic Reliability EREL
Development V	Development Start DSTART	1st Prototype Complete DFPRO	Development Complete DLPRO	Engineering Complexity ECMPLX	Tooling & Test Equip. DTLGTS	Prototype Activity PROSUP
Production VI	Production Start PSTART	First Article Delivery PFAD	Production Complete PEND	Cost-Process Factor CPF	Tooling & Test Equip. PTLGTS	Rate/Month Tooling RATOOL
Actual Cost Data (Mode 7 only)	Average Unit AUCOST	Production Total PTCOST	Prototypes PRCOST	Development Total DTCOST		
Additional Data (Mode 10 only)	Electronic Volume Fraction USEVOL	Structural Weight/ft³ WSCF	Target Cost TARCST			

Notes:

GC 1613 6/80 Note: Inputs in shaded area are optional.

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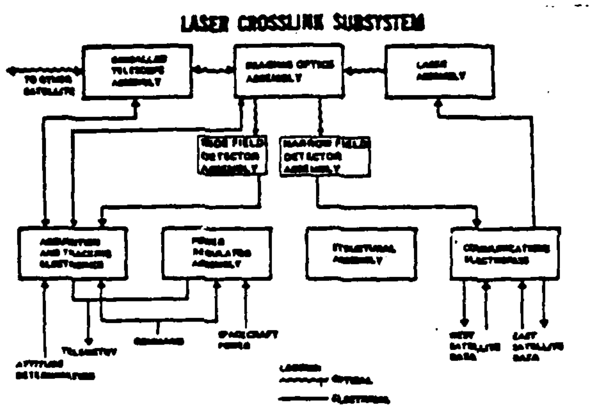
APPENDIX D - CROSSLINK QUESTIONNAIRE

Appendix D contains a sample of the laser and MMW crosslink questionnaires and instructions which were sent to the twelve experts. The questionnaires were based upon generic crosslink designs derived from the literature review, refined by telephone contact with the experts, and finalized after the experts received the questionnaires. The questions covered the required parametric inputs to the RCA PRICE Model.

LASER CROSSLINK SUBSYSTEMS DATA for RCA PRICE MODEL - Part I



dentify estimates as either:
- W = Based upon work on simular components or systems.
- E = Based upon recent work with crosslink components or systems.

	Gimballed Telescope	Imaging Optics	Laser Assembly	Wide Field Detector	Narrow Field Detector
. Volume (in³)	797 in³	2250	440	230	330
	W...E...	W...E..	W...E...	W...E...	W...E..
2. Weight (lbs)	49.5	28.7	25.6	9.2	10.9
	W...E...	W...E..	W...E...	W...E...	W...E..
3. % weight for:					
a. structure	34	33	46	42	39
b. electronics, optics, etc.	66	67	54	58	61
	W...E...	W...E..	W...E...	W...E...	W...E..
4. Quantity needed per satellite to give 7-10 yr system life reliability.	1	1	2	1	1
	W...E...	W...E..	W...E...	W...E...	W...E..
5. Percent new design	None →				
	W...E...	W...E..	W...E...	W...E...	W...E..
6. Cost estimate in 1983 dollars	....	......	....	....	......
	W...E...	W...E..	W...E...	W...E...	W...E..

LASER CROSSLINK DATA CONTINUED -

	Gimballed Telescope	Imaging Optics	Laser Assembly	Wide Field Detector	Narrow Field Detector
7. Would electronics or optics need special cooling considerations (ie., coolant tubes built into circuit boards).	No	No	No*	No	No
	W...E...	W...E..	W...E...	W...E...	W...E..
		* Needs -40°C coldplate			
8. Would there be any special or extensive machining involved in manufacture of antennas, components, and/or support structures	No*	No*	No*	No*	No*
	W...E...	W...E..	W...E...	W...E...	W...E..
	* Structures compatible with precision optics are required but no machining which is unusual to the optics industry				
9. Where would subsystem obtain power?	Power Regulator Assembly (see page 3 of 7) →	→	→	→	→
	W...E...	W...E..	W...E...	W...E...	W...E..
10. What percent of electronics are:					
VHSIC	None →	→	→	→	→
VLSI	None →	→	→	→	→
LSI	None →	→	→	→	→
Hybrid	55%	10%	50%	None	None
SSI/MSI	20%	None	None	25%	20%
	W...E...	W...E..	W...E...	W...E...	W...E..
11. Expected number of P.C. boards	24	8	4	4	5
	W...E...	W...E..	W...E...	W...E...	W...E..
12. Average board size (inches)...	2x3	1x2	3x4	4.5x6.5	6x6.5
weight					
# of layers ...	4	3	2	1	9
	W...E...	W...E..	W...E...	W...E...	W...E..
13. Estimate number of microchips	88	64	48	40	80
	W...E...	W...E..	W...E...	W...E...	W...E..
14. Percent of microchips requiring new design	None →	→	→	→	→
	W...E...	W...E..	W...E...	W...E...	W...E..

LASER CROSSLINK SUBSYSTEMS DATA for RCA PRICE MODEL

	Acq & Trk Electronics	Communication Electronics	Power Regulator Assembly	Structural Assembly	Radiators
1. Volume (in³)	590 W...E...	390 W...E..	1110 W...E...	.... W...E...	...... W...E..
2. Weight (lbs)	21.4 W...E...	11.3 W...E..	46 W...E...	18.5 W...E...	41.8 W...E..
3. % weight for: a. structure b. electronics, optics, etc.	23 77 W...E...	27 73 W...E..	23 77 W...E...	100 0 W...E...	100 0 W...E..
4. Quantity needed per satellite to give 7-10 yr system life reliability.	1 W...E...	1 W...E..	1 W...E...	1 W...E...	1 W...E..
5. Percent new design	None W...E...	...... W...E..	.... W...E...	.... W...E...	...... W...E..
6. Cost estimate in 1983 dollars	.... W...E...	...... W...E..	.... W...E...	.... W...E...	...... W...E..
7. Would electronics or optics need special cooling considerations (ie., coolant tubes built into circuit boards).	No W...E...	...... W...E..	.... W...E...	.... W...E...	...... W...E..
8. Would there be any special or extensive machining involved in manufacture of antennas, components, and/or support structures	No W...E...	No W...E..	No W...E...	No* W...E...	No W...E..
9. Where would subsystem obtain power?	Power Regulator Assembly W...E...	Power Regulator Assembly W...E..	Spacecraft Power W...E...	None Required W...E...	None Required W...E..

*Structure is predominately composite materials requiring casting and forming by unique jigs and fixtures. Nothing unusual to normal composite processes is required

-SER CROSSLINK DATA CONTINUED -

	Acq & Trk Electronics	Communications Electronics	Power Regulator Assembly	Structural Assembly	For [illegible]
.What percent of electronics are:					
VHSIC	None	—	—	Not Required	
VLSI	None	—	—	↓	
LSI	5%	None	None	↓	
Hybrid	5%	15%	None	↓	
SSI/MSI	90%	85%	20%	↓	
	W...E...	W...E..	W...E...	W...E...	W...E..
.Expected number of P.C. boards	50	25	16	None	
	W...E...	W...E..	W...E...	W...E...	W...E..
.Average board size (inches)	3.5x4	3.5x4	8x7	None	
weight					
# of layers	6	6			
	W...E...	W...E..	W...E...	W...E...	W...E..
.Estimate number of microchips	1272	650	250	None	
	W...E...	W...E..	W...E...	W...E...	W...E..
.Percent of microchips requiring new design	None	—	—	—	
	W...E...	W...E..	W...E...	W...E...	W...E..

Estimates based on a subsystem for which the design is complete, engineering hardware has been built, system has been integrated and system tests are currently in progress.

LASER CROSSLINK QUESTIONS -

****
****

15. Would you expect for automation or learning-curve to be a factor in life cycle costs for any portion of the crosslink system? Yes.X. No... Learning curve can be applied to unit cost for production quantities

16. What do you think are the cost drivers in a laser crosslink system? Please put your answer below or on additional sheets.

17. Your answers (estimates) to the 14 questions are based upon one satellite having crosslink communications with two adjacent satellites. If the requirement were changed such that one satellite had to "talk" with just one satellite, could your estimates be decreased by one half? Yes.X. No...?
If "No", why not? Please put answer below or on additional sheets.

18. Your answers given on this questionnaire are based upon equipment and systems which you feel will be available within the next five years. Are there pending developments or technologies which may be introduced that could significantly alter the estimates provided? Yes... No.X.
If "Yes", please explain below or on additional sheets.

19. Are you or your organization currently working on laser systems? Yes.X. No...

20. Please provide any changes, recommendations, insights, and/or general comments below or on additional sheets.

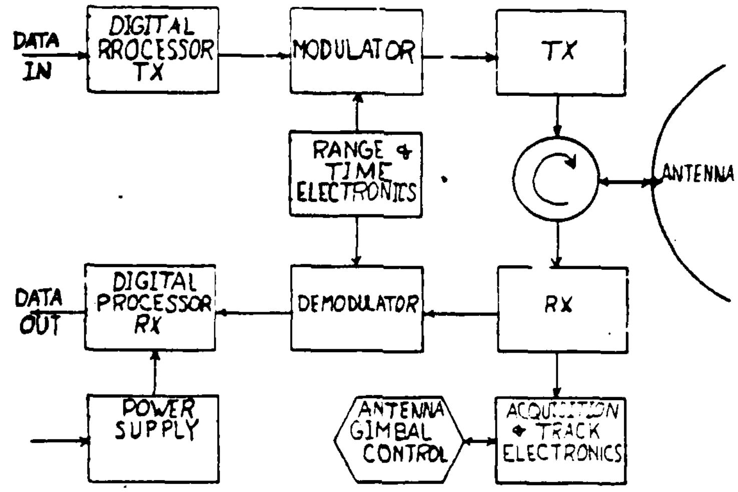
*************** The End of Part I - Thank You **************

16. Cost drivers.
- Building, integrating and aligning precision optics
- Required data rate impact on lasers

Comment

Please note that the laser system includes the "antenna" and its supporting structure. The definition of the millimeter wave system must include the antenna and supporting structure. This is not insignificant if the antenna has to look over large angles in two axes such as is the case in a low orbit to geosynchronous satellite relay link.

MMW CROSSLINK SUBSYSTEMS DATA for RCA PRICE MODEL - PART II



MMW CROSSLINK

Identify estimates as either:

W = Based upon work on simular components or systems.

E = Based upon recent work with crosslink components or systems.

	TX DIGITAL PROCESSOR	MOD-ULATOR	TRANS-MITTER	RANGE & TIME ELECTRONICS	ANTENNA
1. Volume	.26 2"×6"×8"	.01 2"×3"×3"	.07 4"×4"×8"	....	4.44 FT
	W...E.✓.	W.✓.E..	W.✓.E...	W...E...	W...E.✓
2. Weight	2#	1#	10#	....	50#
	W...E.✓.	W.✓.E..	W.✓.E...	W...E...	W...E.✓
3. % weight for:					
a. structure	60	70	60	....	90
b. electronics, optics, etc.	40	30	40	....	10
	W...E.✓.	W.✓.E..	W.✓.E...	W...E...	W...E.✓
4. Quantity needed per satellite to give 7-10 yr system life reliability.	1	1	2	....	1
	W...E.✓.	W.✓.E..	W.✓.E...	W...E...	W...E.✓
5. Percent new design	0	10	30	....	30
	W...E.✓.	W.✓.E..	W...E...	W...E...	W...E.✓
6. Cost estimate in 1983 dollars	50K	300K	750K	....	1,000K
	W...E.✓.	W.✓.E..	W.✓.E...	W...E...	W...E.✓

MMW CROSSLINK DATA CONTINUED -

	TX DIGITAL PROCESSOR	MOD-ULATOR'	TRANS-MITTER	RANGE & TIME ELECTRONICS	ANTENNA
7. Would electronics or optics need special cooling considerations (ie., coolant tubes built into circuit boards).	NO W...E.	NO W...E..	YES W...E...	.... W...E...	NO W...E..
8. Would there be any special or extensive machining involved in manufacture of antennas, components, and/or support structures	NO W...E..	NO W...E..	NO W...E...	.... W...E...	POSSIBLY W...E..
9. Where would subsystem obtain power?	POWER REGULATOR W...E..	POWER REGULATOR W...E..	POWER REGULATOR W...E...	.... W...E...	S/C BUS + POWER REGUL... W...E..
10. What percent of electronics are:					
VHSIC	....	......	....	....	......
VLSI	....	......	....	....	......
LSI	10	......	....	....	......
Hybrid	50	20	....	....	10
SSI/MSI	40	80	....	....	......
	W...E.	W...E..	W...E...	W...E...	W...E..
11. Expected number of P.C. boards	1 W...E.	0 W...E..	0 W...E...	.... W...E...	0 W...E..
12. Average board					
size	6"x8"	......	....	....	......
weight	4 oz	......	....	....	......
# of layers ...	1	......	....	....	......
	W...E.	W...E..	W...E...	W...E...	W...E..
13. Estimate number of microchips	20 W...E.	...... W...E..	.... W...E...	.... W...E...	...... W...E..
14. Percent of microchips requiring new design	0 W...E.	...... W...E..	.... W...E...	.... W...E...	0 W...E..

MMW CROSSLINK SUBSYSTEMS DATA for RCA PRICE MODEL

	RX DIGITAL PROCESSOR	DEMOD-ULATOR .17	RECEIVER .19	ANTENNA GIMBAL CONTROL	ACQ & TRACK ELECTRONIC
. Volume .06	2"×6"×8" W...E.✓.	4"×8"×10" W...E✓.	4"×8"×10" W.✓.E...	2"×6"×8" W...E.✓.	2"×6"×8" W...E✓.
.. Weight	2# W...E.✓.	10# W...E✓.	10# W.✓.E...	2# W...E.✓.	2# W...E.✓.
. % weight for: a. structure b. electronics, optics, etc.	a. 60 b. 40 W...E.✓.	a. 70 b. 30 W...E✓.	a. 60 b. 40 W.✓.E...	a. 60 b. 40 W...E✓..	a. 60 b. 40 W...E✓.
. Quantity needed per satellite to give 7-10 yr system life reliability.	1 W...E.✓.	1 W...E✓.	1 W.✓.E...	1 W...E✓..	1 W...E.✓.
5. Percent new design	0 W...E...	50 W...E✓.	20 W.✓.E...	10 W...E.✓.	10 W...E✓.
6. Cost estimate in 1983 dollars	75K W...E...	500K W...E.✓	500K W...E...	200K W...E.✓.	200K W...E✓.
7. Would electronics or optics need special cooling considerations (ie., coolant tubes built into circuit boards).	NO W...E✓.	NO W...E✓	NO W✓.E...	NO W...E✓.	NO W...E✓.
8. Would there be any special or extensive machining involved in manufacture of antennas, components, and/or support structures	NO W...E✓.	NO W...E✓.	NO W✓.E...	NO W...E✓.	NO W...E.✓
9. Where would subsystem obtain power?	POWER REGULATOR W...E.✓.	POWER REGULATOR W...E.✓	POWER REGULATOR W.✓.E...	POWER REGULATOR W...E.✓.	POWER REGULATOR W...E✓

MMW CROSSLINK DATA CONTINUED -

	RX DIGITAL PROCESSOR	DEMODULATOR	RECEIVER	ANTENNA GIMBAL CONTROL	ACQ & TRACK ELECTRONIC
10. What percent of electronics are:					
VHSIC					
VLSI					
LSI	20	10		20	20
Hybrid	30	30	10	30	30
SSI/MSI					
	W...E ✓	W...E ✓	W ✓ E...	W...E ✓	W...E ✓
11. Expected number of P.C. boards	1	1	1	1	1
	W...E ✓	W...E ✓	W ✓ E...	W...E ✓	W...E ✓
12. Average board size	6"x8"	6x8"	4"x6"	6x8"	6"x8"
weight	4oz	4oz	3oz	4oz	4oz
# of layers	1	1	1	1	1
	W...E ✓	W...E ✓	W ✓ E...	W...E ✓	W...E ✓
13. Estimate number of microchips	20	10	5	20	20
	W...E ✓	W...E ✓	W ✓ E...	W...E ✓	W...E ✓
14. Percent of microchips requiring new design	10	10	0	0	0
	W...E ✓	W...E ✓	W ✓ E...	W...E ✓	W...E ✓

MMW CROSSLINK SUBSYSTEMS DATA for RCA PRICE MODEL

	POWER SUPPLY				
Volume	6×16×17 W...E.✓.	...... W...E..	.... W...E...	.... W...E...	...... W...E..
Weight	20# .... W...E✓..	...... W...E..	.... W...E...	.... W...E...	...... W...E..
% weight for: . structure . electronics, optics, etc.	30 .70..... W...E✓..	.... W...E..	.... W...E...	.... W...E...	.... W...E..
Quantity needed per satellite to give 7-10 yr system life reliability.	1 W...E.✓.	...... W...E..	.... W...E...	.... W...E...	...... W...E..
Percent new design	0 W...E.✓.	...... W...E..	.... W...E...	.... W...E...	...... W...E..
Cost estimate in 1983 dollars	400K W...E.✓.	...... W...E..	.... W...E...	.... W...E...	...... W...E..
Would electronics or optics need special cooling considerations (ie., coolant tubes built into circuit boards).	POSSIBLY ~~No~~ W...E.✓.	...... W...E..	.... W...E...	.... W...E...	...... W...E..
Would there be any special or extensive machining involved in manufacture of antennas, components, and/or support structures	NO W...E.✓.	...... W...E..	.... W...E...	.... W...E...	...... W...E..
Where would subsystem obtain power?	S/C BUS W...E.✓.	...... W...E..	.... W...E...	.... W...E...	...... W...E..

AD-A141 061 ACQUISITION COST ANALYSIS FOR THE NEAR TERM MILITARY APPLICATION OF LASER..(U) AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH SCHOOL OF ENGI.. S W MARLOW

UNCLASSIFIED DEC 83 AFIT/GSO/OS/83D-6 F/G 17/2

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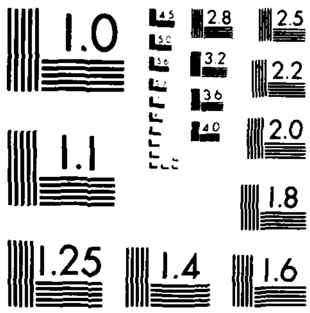

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963 A

MMW CROSSLINK DATA CONTINUED -

	POWER SUPPLY				
10. What percent of electronics are:					
VHSIC					
VLSI					
LSI					
Hybrid	50				
SSI/MSI	50				
	W...E.✓	W...E..	W...E...	W...E...	W...E..
11. Expected number of P.C. boards	1				
	W...E.✓	W...E..	W...E...	W...E...	W...E..
12. Average board					
size	10"x12"				
weight	6 oz				
# of layers	1				
	W...E.✓	W...E..	W...E...	W...E...	W...E..
13. Estimate number of microchips	10				
	W...E✓.	W...E..	W...E...	W...E...	W...E..
14. Percent of microchips requiring new design	0				
	W...E.✓	W...E..	W...E...	W...E...	W...E..

MMW CROSSLINK QUESTIONS -
****
****

15. Would you expect for automation or learning-curve to be a factor in life cycle costs for any portion of the crosslink system? Yes... No... NOT SURE

16. What do you think are the cost drivers in a MMW crosslink system? Please put your answer on the back of this sheet or on additional sheets.

17. Your answers (estimates) to the 14 questions are based upon one satellite having crosslink communications with two adjacent satellites. If the requirement were changed such that one satellite had to "talk" with just one satellite, could your estimates be decreased by one half? Yes... No.✓.
If "No", why not? Please put answer on the back of this sheet or on additional sheets.

18. Your answers given on this questionaire are based upon equipment and systems which you feel will be available within the next five years. Are there pending developments or technologies which may be introduced that could significantly alter the estimates provided? Yes... No.✓.
If "Yes", please explain on the back of this sheet or on additional sheets.

19. Are you or your organization currently working on MMW systems? Yes.✓. No...

20. Please provide any changes, recommendations, insights, and/or general comments on the reverse side.

*************** The End - Thank You ***************

SITUATION DEFINITION and INSTRUCTIONS for the THESIS QUESTIONNAIRE

A. Under consideration are two different satellite-to-satellite crosslink systems. The crosslinks are envisioned as being part of a four satellite communications network with the satellites in geosynchronous orbit. Satellite-to-satellite separation would be approximately 36,000 miles. Further, each satellite has crosslink communications with the two adjacent satellites. For the purpose of this study a 60 GHz MMW crosslink is to be compared with a 532 nm, lamp-pumped Nd:YAG laser crosslink. These systems are to have an on orbit life of 7-10 years and be capable of data transfer rates of 1-10 Mbps. For your input consider equipment and technologies which you expect will be operationally available within the next five years.

B. The questionnaire has two parts, Part I associated with laser and Part II with MMW satellite crosslinks. Each part has seven sheets. Across the top of each sheet you will find the names of five (or less) subsystems corresponding to the names of the subsystems as identified on the attached sketches. Along the left side of the sheet are the questions being asked. The same subsystem names are listed on two consecutive sheets in order to accommodate the 14 questions.

C. Remarks about the questions:

1. Volume refers to how much space the entire subsystem would occupy in or on the satellite. Please include units if cubic feet are not used.

2. Weight refers to the entire subsystem weight. A possible point of deliberation might be how to consider cables, other interface devices, and support structures common to several subsystems. If the interfaces are extremely expensive, consider them as an additional subsystem and identify them as such on Page 6 of either the laser of the MMW section, whichever is appropriate. For other interface devices and support structures, divide the weight equally among the subsystems they connect.

3. This is the percent of total subsystem weight accounted for by structures and electronics.

4. Quantity of a subsystem per satellite might be "2" in many cases since the satellite must "talk" with the two adjacent satellites. However, to gain the needed reliability necessary for the crosslink to be operational for 7-10 years, possibly some subsystems would have redundant back-ups.

5. Estimate how much of the subsystem's design can be borrowed from other operational or test systems vs what percent must be designed from scratch. I might expect designs of certain types of power supplies and antennas to be the same for other, operational

satellites.

6. If you have a fairly accurate cost figure on either the subsystem or some of its components, I can use these as a check on how well the RCA Price Model is doing (at least for that subsystem.) If your cost figures are in something other than 1983 dollars, just state what year dollars they are and I'll make the necessary adjustments.

7. The RCA Price Model is highly sensitive to specialized cooling, especially within electronics packages (ie., having to build circuit boards with coolant tubes embedded into the boards.)

8. If there is special or extensive machining involved, then estimate what percentage of the subsystem's total weight would be made-up of these machined parts.

9. Can the subsystem take satellite power and use it directly, or must the subsystem include components which convert satellite power into its own unique power requirement (ie., AC-DC converter, transformer, phase-shifter, etc.)

10-14. The RCA Price Model is sensitive to costing factors associated with dense, high speed circuitry/electronics.

1-14. The "W" and "E" are confidence factors used to calculate weighted averages.

15-20. The answers to these questions will enable me to run sensitivity analyis on the cost data. These questions are found on Page 7 in Parts I and II.

VITA

Major Stephen W. Marlow was born on 2 January 1943 in Coshocton, Ohio. He graduated from high school in Zanesville, Ohio, in 1961 and attended the Ohio State University from which he received the degree of Bachelor of Science in Chemical Engineering in December 1966. Upon graduation, he received a commission in the USAF through the ROTC program. He completed Air Force's navigator training in November 1967 and electronic warfare officer's (EWO) course in June 1968. While static ed at Wiesbaden AB, Germany, he attended the University of Southern California (Wiesbaden Branch) from which he received the degree of Master of Science in Systems Management in December 1980. As an EWO he served as combat crewmember, instructor, and evaluator in the C-97, F-105G, and F-4E aircraft. His staff experience includes Chief of the Electronic Intelligence Collection Branch at HQ US Air Forces in Europe, Ramstein, Germany, and Chief of the Technical Intelligence/Special Projects Branch at HQ Tactical Air Command, Langley AFB, Virginia. He entered the School of Engineering, Air Force Institute of Technology, in June 1982.

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Title: ACQUISITION COST ANALYSIS FOR THE NEAR TERM MILITARY APPLICATION OF LASER VS MILLIMETER WAVE FOR SATELLITE CROSSLINK COMMUNICATIONS

Thesis Chairman: Joseph P. Cain, Associate Professor of Economics, Department of Operational Sciences

Abstract: Two alternative satellite communication technologies have evolved independently of each other and now seem to be in direct competition for limited R&D dollars. In an attempt to identify which technology is best, this study concentrates on one aspect of satellite communications--intersatellite crosslinks which are capable of processing one to ten megabits of data per second. The analysis effort is further limited to comparisons of procurement costs and factors which influence these costs. The RCA PRICE Model is used to estimate costs of crosslink subsystems. Extensive review (cont'd)

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of the literature, as well as design estimates from experts, is necessary to provide the PRICE Model with sufficient details to produce a credible cost figure. A modified Delphi method is used to aggregate the estimates of the experts. From the cost comparison of laser versus millimeter wave crosslink systems, it seems that millimeter wave with its more mature technology has the cost advantage. However, as laser technology reaches a level of maturity close to that of millimeter wave, the difference in procurement costs should become minimal. There are eleven technical, operational, and cost factors which must be analyzed to adequately determine which technology is "best." Procurement cost analysis by itself does not determine which technology should be continued or stopped.