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Intersatellite Link Design Issues

Richard S. Fuhrmann, Capt, USAF

date: 1985, pages: 110

Master of Science, Telecommunication

University of Colorado

The first Intersatellite Link (ISL) was demonstrated by radio amateurs in 1975. The National Aeronautics and Space Administration (NASA) pursued testing that same year. NASA established links between satellites then in orbit. Sponsored by the United States Air Force and Navy, Lincoln Experimental Satellites (LES) 8 and 9 were launched in 1976 and established the technical feasibility of ISLs.

This thesis explores some of the major design issues involved in ISLs. Two basic approaches are considered, millimeter wave (MMW) and optical. For the MMW approach, the design issues covered were frequency, antenna positioning, acquisition and tracking, antenna type, power amplification, and link analysis. For the optical approach, the design issues covered were laser source selection, optical detection, tracking and acquisition, and proposed systems. The trade-offs involved in system design were also analyzed. Possible applications of ISLs were also discussed.

INTERSATELLITE LINK DESIGN

ISSUES

by

Richard S. Fuhrmann

B.S., University of Miami

A thesis submitted to the

Faculty of the Graduate School of the

University of Colorado in partial fulfillment

of the requirements for the degree of

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Thesis directed by Professor Frank S. Barnes

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DEDICATION

I would like to dedicate this thesis to my son, Christopher Savery Fuhrmann, to whom my thoughts often turn. Whose eyes will see what I can not hope to imagine. By the time he is old enough to read and understand this thesis, it will probably only be of historical interest.

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CHAPTER I

INTRODUCTION

> Communications satellites appeared only 20 years ago. Today they are part of our everyday lives and it is difficult to think how we could do without them. Almost every country in the world is linked by telephone, telex and data services and our television screens show world events as they happen. The world has become a "global village" in which political and cultural frontiers have been crossed as never before.
>
> - Dave Dooling

Our society, and those of other industrial nations, are moving into a new era. This is the era of information. In just the last decade, information storage has moved into the home with a capacity that was once reserved for governments and large companies. We are entering the "information age". The ramifications of this genesis are yet to be witnessed. The fabric of our society may be woven in any number of ways. Commerce, politics, education, the family itself, all may be effected. What is clear is that as this information age matures, telecommunications will be essential. Without a way of moving information, it becomes nearly worthless, much like an industrial complex of factories without rail, truck, or air transportation services.

Data processing and communications are merging. Federal agencies like the Federal Communications Commission (FCC) have difficulty separating the two for the purposes of regulation. The Department of Defense (DOD) has merged these two entities within it's administrative framework. Today, with a small investment in a personal computer and a modem, a private citizen has an audience of thousands through open message systems (electronic bulletin boards), and has access to a multitude of information sources. The global village may be just around the corner.

This progression into an information age will drive telecommunications. Efficient, fast, and accurate world-wide communications will become more and more important. There are many forms that these communications may take. Satellite communications is just one possible form.

Communication satellites are only a few decades old. In all likelihood, we have merely scratched the surface of their potential. Functionally speaking, they have been used as repeaters in the sky. Their capacity and sophistication has grown tremendously over the years, but their function has not changed a great deal. With the advent of satellite to satellite communications, known as intersatellite links (ISLs), this may change.

Intersatellite Links Defined

An intersatellite link is a communications link that directly connects two separate satellites. One satellite could have several links to numerous other satellites. In some of the literature, ISLs have also been called crosslinks.

Since ISLs are space based, at both the transmitting and receiving end, they have built in limitations. They are limited in weight, power, and antenna size, to mention a few. Although these limits are somewhat flexible, the limiting pressures are, nevertheless, present.

The types of traffic that ISLs will carry is up to the system designer. They could carry voice, data, or telemetry, possibly even video. What ISLs will do is transform communications satellites, which today are basically repeaters, into an interconnected global network in the sky. ISLs can be used to connect two separate communications satellite networks expanding the effective coverage for each system. They can be used for space vehicle communications. This will become more important as man moves deeper into space. One of the more near term applications is in telemetry and control systems. The need for a series of earth stations around the globe to control satellites can be replaced by ISLs.

There are certainly many more possible applications for ISLs but those above are some of the more obvious ones.

Approach

In the chapter following, chapter two, the historical aspects will be covered. The first part of this chapter will deal with satellites in general. In the second part, the history of ISLs are outlined. From this chapter, an appreciation for the rapid growth of communications satellites and associated technologies, should develop in the reader.

The third chapter deals with millimeter wave (MMW) ISL technology. This technology and optical technology are the two currently being considered. Some of the design issues and considerations for a MMW ISL are discussed.

In the fourth chapter, optical ISL technology is reviewed. Basic design issues for optical ISLs are outlined. Some of the generalities associated with optical laser communications are also mentioned.

In the fifth chapter, the trade-offs alluded to in chapters three and four are expanded upon. Factors such as antenna size, power transmitted, power received, range, and frequency are compared.

In the sixth chapter, some of the possible applications of ISL technology are reviewed. Possible impacts on mobile satellite systems, manned space missions, and global networks are mentioned.

The final chapter contains the conclusion. In this chapter the key areas of the previous chapters are summarized.

> Just as communications satellites are said to be analogous to repeater towers in the sky, ISL could be said to be analogous to "cable in the sky", providing service and connectivity over regions extending beyond the coverage region of a single satellite. Thus ISLs between geostationary satellites over different oceanic or continental regions may be considered a vital part of an integrated global satellite communications system and network and a natural progression in the evolution of the satellite communications technology.
>
> - Ashok K. Sinha

CHAPTER II

HISTORICAL PERSPECTIVE

The first thing that becomes apparent when studying satellite systems is that the field is both young and explosive. The "history" of satellites is not yet three decades old, yet the advances in this technology have been remarkable. Predicting the success or failure of new technologies, in this type of environment, is precarious at best.

Communication Satellites

The first satellites were very primitive. Sputnik I, launched in 1957, was mans first artificial satellite. It was basically a radio beacon. In 1958 Score (NASA) was launched into a low orbit. It was a simple broadcast type satellite. A tape recording of President Eisenhower's Christmas message was carried on-board and was transmitted. Echo and Echo II (NASA), launched in 1960, were passive reflectors. They were aluminum coated balloons by which radio signals from earth were reflected and received back at earth (1,2).

In 1960 the first repeater satellite was launched. Courier (DOD) was what it´s name suggests, a courier. It received and stored up to 360,000 teletype words and rebroadcasted them farther down it´s low altitude route. It´s operation lasted 17 days (1).

The first repeater satellite, Telstar (AT&T), was launched into an elliptical orbit on 10 July 1962. It was able to receive and transmit simultaneously in the 4/6 GHz. At it´s highest orbital position, it was able to provide communications between the United States and Europe. Earth stations were constructed in the United States, the United Kingdom, and France. This satellite was in successful operation for about five months during which telephone, television, facsimile, and data were transmitted (3) . Two weeks after launch, millions of Europeans and Americans watched as a two way sound and video conversation took place across the Atlantic. Perhaps the birth of the "global village" (2). By February of 1963, the satellite had deteriorated to the point that it was beyond use.(3)

Later that same year (1962) Relay (RCA and NASA) was launched. The notable features of this satellite, over previous ones, were it´s improved travelling wave tube system allowing, 12 watts of output power (previous systems were in the range of 2-3 watts), and it´s redundant communications repeater. (3)

The first geostationary satellite, Syncom (NASA), was launched in 1963. The up and down link frequencies changed to 7/18MHz. During this time a method of launching a satellite into geostationary orbit had evolved. The satellite was launched into an elliptical orbit, then an apogee motor was fired, altering the orbit to a circular one with a radius equal to that of the apogee of the elliptical orbit. The learning process was not without problems. The first experimental Syncom satellite was lost after the firing of it´s apogee motor. A second Syncom satellite was launched later that year, attained geostationary orbit, and communications were established. (3) It was used to transmit the Tokyo Olympic Games in 1964 (1).

During these early years it became clear that for commercial exploitation of satellites to continue, cooperation on an international level would be necessary. To this end the International Telecommunication Satellite Consortium (INTELSAT) was formed. The primary aim of INTELSAT was to establish a satellite communications system on a global level. Thus the Intelsat series of satellites began.

In 1965 Early Bird (Intelsat 1) was launched into orbit over the Atlantic. It was the worlds first commercial communications satellite. It had a 240 voice channel capacity and an output power of 40 watts (1). It was designed for a life of only 18 months but remained active for a surprising four years.(2

The second series of Intelsat satellites was initiated in 1966. The first of the series failed to make it to it´s desired orbit. A second satellite was launched in January of 1967 and remedied the failure. This series had greater bandwidth capability, and was the first commercial multiple-access multidestination satellite. (1,3) The circuit cost of Intelsat II was $10,000, a drop of $20,000 from Intelsat I. (2)

The Intelsat III series carried two wideband repeaters and was the backbone of the first global system. It had a capacity of 1200 voice circuits and an output power of 120 watts. The per circuit cost dropped to $2,000. This series of satellites used a mechanically despun horn antenna. The previous series of Intelsat satellites used omni-directional antenna, thus much of the radiated power was lost to space. Long life space rated motors were required to accomplish this, a significant advancement.(1,2,3,) Intelsat IV, in 1971, saw a further increase in power to 400 watts and 4000 voice circuits or two color television circuits. Of interest is that the Intelsat IV series had two spot-beam antennas. In addition, a milestone was reached, Intelsat IV was limited by available frequencies rather than power. Intelsat IVA (1975) employed more spot beams and increased the capacity to 6,000 circuits while keeping the cost at $1,000 per circuit(1,2).

Intelsat V (1980) saw a continued increase in the capacity to 12,000 telephone circuits and two color television channels. Intelsat VA, an improved version of Intelsat V, was designed with a capacity of 15,000 voice circuits and two color television circuits. (4)

Intelsat VI, scheduled for launch in 1986, will have a capacity of 33,000 voice circuits as well as four television circuits. It will have up and down links in the 6/4 and 11/14 GHz range.(4)

INTELSAT is, by no means, the holder of a monopoly when it comes to satellites. In the early 70's, the low cost per circuit generated interest in domestic satellites which resulted in the U.S. Federal Communications Commission's Open Skies Policy in 1972. Canada's ANIK satellite, a domestic satellite, had already demonstrated a return on investment unprecedented in the industry up to that time (1). WESTAR (Western Union), launched in 1974, was the first U.S. domestic satellite.

This is certainly not an all encompassing summary of satellite history. Military and scientific satellite ventures have not been discussed. However, the reader should be able to gain an appreciation for the advances that have been made. The methods for geostationary orbit have been developed. Antenna design has progressed from omni-directional to directional antenna ie. horn, dish, spot beam, and even phased array. Technical problems of power production have been refined. The effect of radiation on semi-conductors is much better understood. Also worth noting is the increase in the length of the development time for satellite systems. Systems are becoming increasingly complex. And yet, with as far as man has advanced in the last few decades, at best, satellites are in their infancy.

Arthur C. Clark, who in 1945 originally proposed geostationary satellites in a Memorandum to the Council of the British Interplanetary Society, spoke at the ceremonies finalizing the formation of INTELSAT in 1971,

> For today, gentlemen, whether you intend it or not, whether you wish it or not - you have signed far more than yet another intergovernmental agreement. You have just signed the first draft of the Articles of Federation of the United States of Earth.

Intersatellite Links

The first ISL was demonstrated by radio amateurs in January of 1975 . The link was between AMSAT/OSCAR-7 and AMSAT/OSCAR-6 (5). The antenna of these small satellites were non-directive. A signal was sent to OSCAR-7 at a frequency of 432.15 MHz and was relayed back to earth at 145.95 MHz. Some of that signal was received by OSCAR-6 and was repeated to earth at a frequency of 29.50 MHz. The transponders on these satellites were linear. Thus, the signal from OSCAR-7 was not filtered out. Angle, frequency and timing of the receive signals were not tracked by the satellites. These satellites were in polar orbit and the ISL was available only when the satellites were in view of each other.

NASA pursued testing of ISLs with the ATS-6 satellite. In April of 1975, a link was established from a low orbit satellite, GEOS-3, up to ATS-6 (S-band 2.25 GHz) and then down to an earth station (C-band 4 GHz). GEOS-3 was equipped with four low gain antenna. Ground command selected the antenna with the best orientation.

A similar link was established in June 1975 with a weather satellite, NIMBUS-6. Transmission was through a steerable 15 dB antenna. In both of these cases the ATS-6 satellite had to be continuously reoriented in order to track the low altitude satellite with which it was communicating. ATS-6 had a one degree beam (30 ft diameter paraboloid at approximately 2.25 GHz). This beam was maintained to within 0.1 degrees of the line of sight for a successful link.

In July 1975 , ISLs were established, as part of the Apollo-Soyuz Test Project, between the Apollo Service Module and the ATS-6 satellite. Again, the ATS-6 had to be continuously repositioned to maintain the link. This link provided two-way communications as well as a data link for 55 minutes of each 87 minute orbit (5).

In the cases above, ISLs were established using antenna not specifically designed for the job. The satellites had to be reoriented. This was not the case with Lincoln Experimental Satellites (LES) 8 and 9. LES 8 and 9 were sent into orbit on 15 March 1976. This project was sponsored by the US Air Force and

Navy. The satellites carried a pair of millimeter wave (MMW) ISL systems into geosynchronous orbit. The original plan was to launch both a laser and a 55 GHz ISL system. Because of the risks involved in these leading edge technologies, an ISL system in the 36-38 GHz range was chosen. The LES 8/9 systems allowed for acquisition and tracking without disruption of the rest of the systems, ie. uplink and downlink. The success of the ISL between LES 8 and 9 demonstrated the feasibility of ISLs (6). LES 8/9 will be discussed in more detail in chapter three.

CHAPTER III

MILLIMETER WAVE (MMW) ISL

The phrase "millimeter wave" refers to the wavelength in the millimeter range, namely 10mm - 1 mm. This wavelength corresponds to the frequencies from 30 to 300 GHz. Frequencies in this range are also referred to as extremely high frequency (EHF) and the Ka band.

The birth of millimeter wave technology was stimulated by work in molecular spectroscopy and military radar. A communications system in the EHF range was developed by Bell Systems in the 1950's. With the advent of optical communications, this line of interest was discontinued. As problems with optical communications began to surface (attenuation due to smoke, dust, etc.) MMW technology enjoyed a resurgence. (6)

Millimeter wave technology shows great promise, especially in the near term, as a candidate for ISL applications. Lincoln Experimental Satellites 8 and 9 (LES 8/9) demonstrated that MMW ISLs are feasible. In this chapter some of the MMW ISL design issues will be explored. The approach will be to discuss LES 8/9 design issues, almost as a case study, while expanding on each area as needed. Some of the characteristics of the LES 8/9 ISLs were:

Table 1. Selected characteristics of LES 8/9 ISLs.(5)

data rate	10 or 100 kbps
modulation	DPSK
frequency	36.84/38.04 GHz
transmitter	solid-state IMPATT diodes (Si based)
output pwr	-3.7 dBW (0.43 W)
receiver	GaAs diodes - balanced-mixer
antenna	18in. paraboloid and reflector, feed at focus
half-power beamwidth	1.2 degrees

Frequency

The selection of frequencies in any satellite system is as much a political/policy decision as a technical one. Space is an international resource, subject to pressures and restrictions on an international level. The United States, as a member of the International Telecommunications Union (ITU), must register both geostationary orbital positions and frequencies with the International Frequency Registration Board (IFRB).

The IFRB is a part of the ITU. It was created in 1947 to alleviate and prevent interference between radio systems. This problem is as real today as it was in 1947. With the advent of satellites, the IFRB also took on the job of registering geosynchronous orbital positions. Again, in order to prevent interference between satellites.(7)

The following frequencies were allocated for ISL use at the World Administrative Radio Conference in 1979 (WARC-79). All of these frequencies must be shared with terrestrial systems, however, in the bands above 54GHz, atmospheric attenuation is high, thus, terrestrial interference is not a problem.

Table 2. WARC-79 allocated ISL frequencies.

Frequency range (GHz)	Bandwidth (GHz)
22.55-23.55	1.00
32-33	1
54.25-58.2	3.95
59-64	5
116-134	18
170-182	12
185-190	5
TOTAL	45.95

The frequencies chosen for the LES 8/9 ISLs were 36.84/38.04 GHz. The original concept for these experimental satellites included both EHF and optical links. The optical portion of the experiment was dropped. The state-of-the-art in laser diode technology in 1971 made the proposition an extremely high risk. The EHF link was originally going to be in the 55 GHz range. This frequency is at the lower end of the oxygen absorption band (see figure 1). This would have afforded a degree of isolation from terrestrial systems while still permitting testing of the ISLs from special purpose earth stations. Again, because of the technical limitations at that time, lower frequencies were chosen.

There are a number of factors which tend to favor higher frequencies (54GHz and up) as the frequency of choice for ISLs. These factors are bandwidth, antenna size, frequency/orbital congestion, and security/isolation.

If you assume that the bandwidth capable of being transmitted on a carrier frequency is some fixed percentage of that frequency, then it would follow that higher frequency carriers can support greater bandwidths than lower frequency carriers. C-band frequencies (about 3-7GHz) can support bandwidths of approximately 500 MHz. This is roughly 10% of the carrier. Using this figure, a 60 GHz carrier could support a bandwidth of 6 GHz. This is 12 times the bandwidth of a C-band carrier. This kind of increase would have a great influence on the cost effectiveness of the system (8). In addition, referring to the table above, the bandwidths allocated by the ITU at higher frequencies, is more plentiful.

Another factor which tends to favor the higher frequencies is antenna size. This is especially true for satellite systems which are limited in size and weight by the launching system. As frequencies increase, all else being the same, antenna size decreases (see Table 3). Since size and weight generally translate to cost, the financial aspects also enter into the decision process.

Table 3. Antenna size for various frequencies and beamwidths. (3)

Frequency (MHz)	Antenna diameter (m) 4 deg.	1 deg.
100	52.20	208.00
500	10.44	41.70
1000	5.22	20.80
5000	1.04	4.17
10000	0.52	2.08
50000	0.11	0.42

A third factor which tends to push development of the higher frequencies is orbital and frequency congestion. Any system that relies on the free space propagation of radio waves risks the problems associated with interference. The careful selection of frequencies is essential. The proximity of other systems using the same frequency is also a consideration. Satellite communication systems are no exception. As more and more satellites are placed into orbit, especially in positions that serve the industrial nations, more and more pressure for an expanded radio frequency spectrum exists.

Interference between satellites has been avoided through the judicial selection of orbital slots. Those systems utilizing the 6/4 GHz band can be located no closer than 4 degrees along the orbital arc. This limits the number of slots covering the "new world" to 15. Satellites utilizing the 14/12 GHz band also have a 4 degree minimum separation requirement, however, those broadcasting television on that band must be 8 degrees apart. The separation requirement at higher frequencies is much smaller due to narrower beamwidths. In the 30/20 GHz band the separation need only be 1 degree.(2)

Thus, the development of the higher frequencies will have a two part effect on satellite frequency congestion. Firstly, with higher frequencies, the orbital separation need not be as great, so more satellites can be placed into orbit. Secondly, as new frequencies become available, those satellites utilizing them can be interleaved with existing satellites. Although we have been discussing the frequency congestion problem in terms of up and down links, the same principles apply to intersatellite links.

Atmospheric attenuation at the higher frequencies is a limiting factor for up/down links. It is a bonus for ISL applications. In the range of 60 GHz there is approximately 9 GHz of bandwidth allocated (table 2). Also in this region of the spectrum, atmospheric attenuation, due to oxygen and water molecule absorption, effectively isolates the system from the ground (9). Terrestrial based interference, jamming, and interception is essentially eliminated. This has obvious advantages in a military application.

In the case of satellite systems, much of the intelligence gathering revolves around the telemetry signals. By utilizing ISLs, a single satellite can be used to relay telemetry signals to a number of other satellites. NASAs Tracking and Data Relay Satellite System (TDRSS) program is based on this concept. NASA was motivated in this direction for economic rather than security reasons (10). For military purposes, these other satellites can effectively appear "dead"

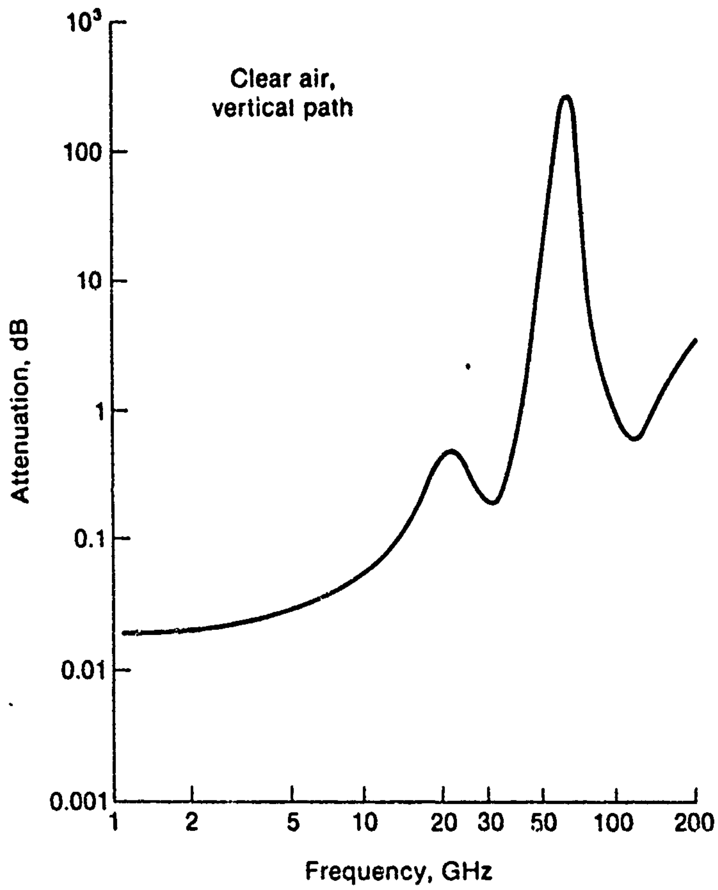

Figure 1. Atmospheric attenuation vs. frequency. (8)

until needed. Interception is not eliminated since it can be accomplished by positioning a satellite within the line of sight, however, it significantly increases the cost of interception.

One disadvantage in frequencies in the 60 GHz band is a loss of flexibility. Should there be a catastrophic failure in the down/up link, it could be possible to use the ISL as a backup. However, the attenuation at these frequencies might preclude this option. For commercial applications, the 22.55-23.55 GHz or the 32-33 GHz bands might be considered. Yet, these bands are limited in bandwidtn. A balance would have to be struck between the higher vs. lower bands and the confidence in the up/down link.

To summarize, the frequencies used for the LES 8/9 satellites were chosen for reasons of technical short fall. For MMW ISLs the 60 GHz range holds promise. At this range 9 GHz of bandwidth is available. The antenna size is reasonable. And it offers a certain amount of freedom from earth based interference, jamming, and interception. (9)

Antenna Positioning

The method used for positioning the antenna will vary from application to application. The degree of accuracy would depend greatly on the beamwidth as well as the sensitivity of the receiver. The angles through which the antenna must position varies a great deal depending on the specific mission of the satellite. If the ISL were between isolated satellites, and relative positions are basically constant, then the required angular travel of the antenna could be minimal (11). The accuracy could be more critical. On the other hand, if the ISL were between two colocated satellites, their relative positions, in terms of angle, would be much less constant. The angular considerations would then be more of an issue and accuracy, while still important, would tend to be less critical. The gain associated with narrow beamwidths would not be necessary when distances are not great. A much broader beam would be feasible (see figures 2 and 3).

In the case of LES 8/9, positioning of the ISL antenna was accomplished by an "elevation-angle-over-azimuth biaxial crosslink drive (BCD. biax)" (5). The biax positioned a reflector in such a way as to steer the beam (see figure 4). The antenna could be pointed in any desired direction within the range of +/- 10 degrees elevation and +/- 52 degrees azimuth (12). This type of antenna design did not require RF rotary joints nor flexible wave guide. However, it did weigh more than a standard steerable paraboloid and two precise reflective surfaces had to be protected from distortion rather than one. At high frequencies, the

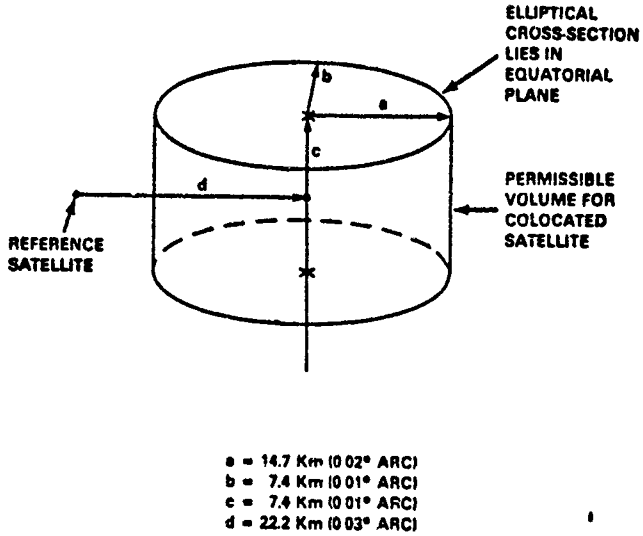

Figure 2. Geometry of colocated satellites. (11)

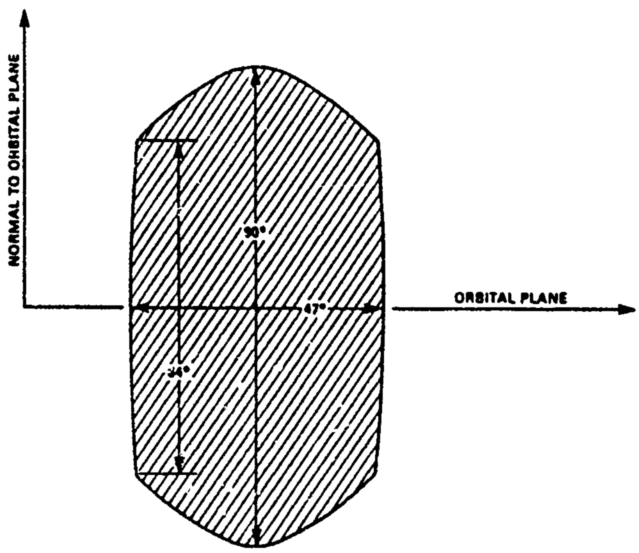

Figure 3. Scanning angles for colocated satellites (11)

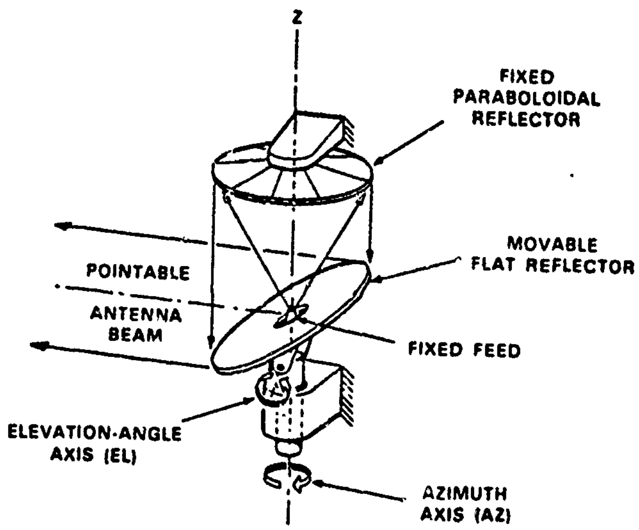

Figure 4. LES 8/9 antenna. (5)

surface of the antenna becomes very important. Protection against thermoelastic deformation was provided.

The biax drive required it's own thermal-control system since it was located outside of the main satellite body. A minimum temperature of 5 degrees C was maintained, using active heaters while the biax was shadowed. When exposed to the sun, passive thermal radiators prevented temperatures from rising higher than 35 degrees C. "This daily cyclic requirement for heater power may prove to be the limiting factor in the life of the biaxes, and therefore of the ISLs." (5) Due to the degradation of the radioisotope thermoelectric generators (RTGs) the available power will eventually diminish to the point that the biax heaters will have to be left off. Some of the biax components would likely suffer permanent damage due to the ensuing thermal stress.

The biax system worked satisfactorily in orbit. LES 8/9 was an experimental satellite. The technology involved at the time was on the leading edge. The level of sophistication may have been greater than necessary.

> In retrospect, it might have been made somewhat simpler. In our zeal to assure success of the LES-8/9 ISLs, we demanded positive knowledge of the position of the 1.2 degree wide beam to within a count of 0.04 degrees in each angle. This requirement corresponds to measuring AZ to 0.04 degrees and EL to 0.02 degrees. This degree of refinement allowed us to make very fine-grained measurements of the performance of the angle-tracking system. Were we to do this job again, however, we might settle for a coarser readout of beam position. We might also use stepping-motor actuators for AZ and for EL instead of torque motors and tachometers required by direct drive systems.(5)

Acquisition and Tracking

In systems where large coverage (large beamwidth) antenna are used, such as horn antenna used for earth coverage, the level of sophistication in positioning the satellites antenna need not be great. When beamwidths of a few degrees are used, the problems in aligning the beam become more serious. This is the case for ISLs, especially ISLs between isolated satellites.

In general, the acquisition or alignment of the ISL takes place in two steps. First an initial orientation, then a final acquisition. For the initial orientation, the attitude of the two satellites must be adjusted to within range of the ISL antenna positioning system. Then the initial positioning of the ISL antenna can be made. The angular search will depend on the accuracy of the data on the orbiting position and attitude control. A frequency search to get "in the ball park", again, depends on the knowledge of the orbital parameters. The relative motion between the two satellites can give rise to doppler shifts in frequency.(13)

Once everything is reasonably close, a final acquisition can be made. The antenna on one satellite is held to a fixed pointing angle and frequency. Then the antenna on the other satellite is stepped through a series of pointing angles and a frequency search is conducted at each step. The frequency search should cover a band several times larger than the frequency uncertainty. If acquisition is not accomplished the first antenna is shifted to the next step and the process is repeated. Each step should be on the order of a beamwidth or less and the range of the search should be several times the pointing uncertainty (13).

In the case of LES 8/9, a spatial uncertainty of 2.1 degrees by 3.5 degrees was planned for. The steps for acquisition were in 0.7 degree increments. The beamwidth was 1.2 degrees. The frequency search range was based on an uncertainty of +/- 5 KHz.

The 0.7 degree boresight tolerance was possible through the use of electrically lobed feedhorns and autotrack receivers. In addition, a Pr/No > 46 dB was necessary for link integrity (12). Should the antenna boresight stray beyond 0.7 degrees, the scan mode could be initiated on command.

> The sequential-lobing arrangement for angle-tracking in the LES-8/9 ISLs has proved to be entirely satisfactory. Little use has been made of the rectangular-spiral-scan provisions for acquisition in angle. That feature was tested during the first few weeks after launch. It has been our experience, however, that the satellite's 1.2 degree wide antenna beams can be placed by command within several tenths of a degree of alignment with the line-of-sight, after which pull-in and autotrack in angle are easily achieved. (5)

The beam steering commands were originated by an earth based computer located at the Lincoln Experimental Satellite Operations Center. Commands were based on accurate ephemerides for the satellites as well as telemetry data on attitude and reference coordinates. With advances in on-board processors and computational capability, this next generation of ISL satellites will provide their own open-loop pointing instructions. (5)

The necessity of the autotrack-in-angle depends on several things. How reliable is the attitude control system of the satellite? How well can the ISL antenna be pointed without this capability? Should any variations in the attitude of the satellite develop, an autotrack capability could keep the system functional without interruption. This pointing system could also be used to gain information on the attitude and telemetry of the satellite should those monitoring systems fail for some reason. The level of refinement of the LES 8/9 tracking system is probably not justified for commercial use. (5)

Phased Array Antenna

The above discussions were primarily based on conventional antenna. A phased array system is a possible option that can be considered. However, when you compare the data rates (parabolic vs. phased array) in terms of transmitter power, weight, and aperture size, the paraboloid system is favored in most categories at most data rates.

With the present technology, phased array systems require more power than paraboloid systems at all data rates, everything else being equal. This is an important issue since the power production in a satellite system is often limited.

In terms of aperture size, the phased array system has an advantage. However, in terms of weight, the paraboloid is favored at data rates above 10,000-12,000 bps. (13)

Power Amplifiers

> The decision (made in the very early 1970s) to develop solid-state power amplifiers for the LES-8/9 ISLs was inescapable at the time. Advances in traveling-wave-tube technology might lead to a different decision today.(5)

The LES 8/9 transmitters utilized eight identical IMPATT diodes per transmitter. Each diode was not equally taxed, the five nearest the output were stressed more heavily than the three nearest the input. The output of a 4 stage preamplifier was split 4 ways to feed 4 power amplifiers. The outputs were then combined coherently. The ISL transmitters experienced no failures. However, a similar transmitter on LES 9, which used the same design, did experience failures in two of the output-amplifier diodes. This is in comparison to the 32 diodes in service, 20 in heavy service.

LES 8/9 were launched on 15 March 1976. As of 31 December 1982, the on-time, in hours, for the EHF transmitters were:

Table 4. Hours of operation-LES 8/9 (5)

	LES-8	LES-9
Dish antenna	31,800	16,300
Horn antenna	2,600	11,600
estimated hours of ISL operation		
LES-8 to LES-9	2,175	
LES-9 to LES-8	1,800	

At present, solid-state power amplifiers do not have the necessary output nor efficiency to operate in the most promising frequency range (60 GHz). Development of high power, high efficiency IMPATT diodes is underway.

IMPATT diodes are the most promising of the solid-state devices, for ISL application, presently known. In the 10 to 300 GHz range, they are the leader in power output both theoretically and practically.

The relationship between power and frequency for the IMPATT diode is 1/f at the lower frequencies and $1/f^2$, or worse, in the millimeter wave frequency range. IMPATT diodes based on GaAs seem to have an advantage over Si based diodes, both in power and efficiency, below 50 GHz. Si based diodes are favored at frequencies above 94 GHz. In the frequency range between 50 and 94 GHz, the performance comparisons are uncertain. At 60 GHz, there is some indication that GaAs will be favored. Presently (1984-1985) a 0.8 W power range, with an efficiency of 6-9 percent, is attainable. NASA is presently sponsoring contracts for 1 W, 15 percent efficient, highly reliable 60 GHz IMPATT diodes. (14)

Transmitter technology in the 60 GHz range is advancing in the area of travelling-wave-tube (TWT) technology with generally more promise than is the case with solid-state. TWTs offer much higher efficiency, bandwidth, and power. For the near future, only TWTs offer enough potential power for applications requiring long-distance and large bandwidth. (9)

In 1977 a 50 GHz coupled cavity tube with 400 watts of power and a 5 percent bandwidth was reported. If you scale the power, to account for the higher frequency, by a factor of $1/f^3$ and reduce it again by a factor of 3 to allow for conservative design, about 75 watts can be expected at 60 GHz. NASA has a program underway for the development of just such a TWT. The target is a 75 watt, 40 percent efficient TWT with a 3 GHz (5%) bandwidth. (9)

The choice of power amplifier will depend on frequency of operation, bandwidth, and power (distance). For power requirements in the 10 watt range, it is predicted that IMPATT based solid-state amplifiers may be competitive with TWTs (14). For most ISL applications, TWTs are the most likely choice for the near future.

Link Analysis

In the 60 GHz range, a commercial channel of 274 Mbps can be supported over very long ranges. Power requirements would be between 5-100 watts with reasonable antenna sizes (9). Optimization of certain parameters, when possible, could yield greater efficiencies (see table 5). The separation between satellites in table 5 was only 1843 km or 2.50 degrees. In the case of LES 8/9 the separation was about 45,300 km or 65 degrees. Table 6 shows the link calculations for LES 8/9.

Table 5. Link power budget (9)

ISL frequency = 61.500 GHz
bit rate = 274 Mbps
bits/symbol = 2

Transmitting satellite	
output pwr, dBW (0.076 watts)	-11.10
antenna gain, dB (1.2 m, 0.28 deg)	55.22
feed loss, dB	-3.00
EIRP, dBW	41.05
antenna point error, dB (0.05 deg)	-0.30
System losses	
margin, dB	-0.00
aging effects, dB	-1.00
random var. of elements dB	-1.50
prop. loss, dB (1843 km)	-193.53
Receiving satellite	
antenna point error, dB (0.05 deg)	-0.30
feed loss, dB	-2.00
antenna gain, dB (1.2 m, 0.28 deg)	55.22
Rx carrier pwr, dBW	-102.36
Rx noise pwr density, dBW/Hz (Tr=525)	-201.40
bandwidth, dB	84.38
uplink noise (Eb/No)	1.11
Rx noise power, dBW	-117.02
Link C/N power ratio, dB	13.55
implementation loss, dB	-1.00

Table 6. Link calculations for LES 8/9 ISLs (5)

	LES 8 to 9	LES 9 to 8
separation	65 deg	65 deg
range	45,300	45,300
frequency (GHz)	38.04	36.84
polarization	LHCP	RHCP
Pt (dBW)	-3.5	-4.0
Gt (dBI)	42.9	42.6
path loss (dB)	-217.2	-216.9
Gr (dBI)	42.6	42.4
Pr (dBW)	-135.2	-135.9
No [dB (W/Hz)]	-197.3	-196.9
Pr/No (dBHz)	62.1	61.0
min Pr/No to hold phase lock (100 kbps) (dBHz)	48.0	48.0
loop margin (dB)	14.1	13.0
min Eb/No for a BER of 10^{-4}	8.8	8.8
data rate [dB(bps)]	50.0	50.0
link margin	3.3	2.2

Summary

Some of the major design issues for MMW ISLs were discussed in this chapter. These issues were frequency, antenna positioning, acquisition and tracking, antenna choice, power amplification, and link analysis.

In the design of any ISL there will be many trade-offs to be considered. In some areas, specific applications will determine the choices and levels of sophistication needed. In others, the level of technology available at the time may determine some choices. This was seen, to some degree, with LES 8/9. The areas covered in this chapter should give the reader an understanding of some of the concerns that would need to be addressed when planning an ISL.

CHAPTER IV

OPTICAL INTERSATELLITE LINKS

Intersatellite link technology is still in a developmental stage. This is especially true when discussing optical or laser ISLs. Since the first laser was demonstrated in 1960, there has been a great deal of interest in it's applications in communications. By 1965 the United States Air Force Avionics Laboratory was studying laser communication concepts. In 1970 the Laser Communication Program was established. The goal was to develop a one gigabit (10^9 bits) per second communications system utilizing lasers. In 1980 the USAF demonstrated an airborne system with this capacity. (6) In this chapter some of the design issues of optical ISLs will be discussed.

The electromagnetic spectrum, from ultra-violet to infra-red, can be defined as the optical spectrum. This corresponds to the wavelengths from 0.3 to 300 micrometers. While these sizes are quite small in relation to physical objects, they are large in relation to atomic distances. Thus, the electromagnetic wave theory holds even in the optical range. Optical communication systems are usually designed for operation in media other than the atmosphere. At optical wave lengths, the atmosphere can be very disruptive. In space, however, optical communications are a natural candidate for many applications.

The material properties are different at this frequency than they are in the radio frequency range. For instance, metallic conductivity is considerably lower. Obvious, even to the casual observer. Also, since the energy per photon is equal to Plank's constant times frequency, the number of photons per unit of power decreases with frequency. In other words, the signal/noise photon ratio decreases with higher frequencies, given the same power level. These are some of the more important properties which govern how optical communications may be utilized. (3)

Laser Source

In a previous chapter, the theory that the capacity of a carrier frequency is some percentage of that frequency, was applied to millimeter wave frequencies. The higher the carrier frequency, the greater the theoretical capacity in the form of bandwidth. This argument can also be extended to include lasers. Lasers operating in the 10^{14} Hz range have a 10^5 advantage over C-band frequencies. This represents a 90 dB power advantage as well as a 10^5 increase in bandwidth. (8) Lasers also afford excellent isolation. This is important for the military for security as well as anti-jamming reasons. For civilian applications, isolation minimizes interference and allows frequency reuse.

Table 7. Wavelengths of some optical sources. (15)

Laser Source	Wavelength
CO_2	10.6 micrometers
Nd:YAG	1.06 micrometers
GaAs	0.9 micrometers
HeNe	0.63 micrometers
FD Nd:YAG	0.53 micrometers

Although there are advantages to higher frequencies, the selection of the laser source will be governed by many other factors. Factors such as power output, efficiency, modulation techniques, pulse width, and repetition rate. Of critical importance for space applications is reliability. A system designer might "sacrifice" a great deal in other area's for the sake of longer life and reliability.

The choice of the optical source will depend heavily on the maturity of the technology evolving around that specific choice. Choice X may have intrinsic advantages over choice Y, but Y may be more developed at the time. Materials of various types have been used, gases. liquids, semiconductors, to mention a few. The material chosen will determine the physical properties (frequency), the efficiency of operation in terms of power, and the auxiliary systems required to support the laser. For the smaller, lightweight, but low power solid-state diode laser, a method of combining the power of several diodes, by an array configuration, is developing. (8)

Beam spreading is a major concern when dealing with arrays. Any divergence, as elements are added to the array, will dilute the power. A perfect combiner will add the output of a series of diodes without increasing the beamwidth. In this way the power is added directly. (8)

In the last few years, considerable progress has been made with diode arrays. In 1982 a coupled multiple striped quantum well injection laser was reported with a peak power output of 2.1 watts (16). In 1984 a quantum well heterostructure laser was reported with a 1.6 watt peak power (17). In addition peak power levels of 200 and 265 mW per facet have been attained (18,19). Clearly, it will not be long before the diode array will be competitive with Nd:YAG lasers in power output. If we scale the 2.1 W peak power buy a factor of three to allow for conservative design, a 700 mW peak should be attainable.

Judging by the literature, the more popular laser sources are GaAs, GaAlAs, and the Nd:YAG. The Nd:YAG was selected for development in the early 1970's by the U.S. Air Force's LASERCOM program. This decision was based on the state of development of the Nd:YAG laser, the ease of modulation, simplicity of direct detection, and the overall link efficiency as compared with the CO_2 laser (20). In recent papers from Lincoln Laboratory the GaAs and GaAlAs have been proposed as laser sources for optical heterodyne intersatellite links. (21, 22)

It would be difficult to say whether one type was better than another, it all depends on the application involved. For instance, the Nd:YAG has a greater power output (0.5-1 watt) than individual GaAs or GaAlAs lasers (40 milliwatts). The GaAs type lasers are more efficient (5-10 percent) than the Nd:YAG (0.5-1 percent) as well as potentially more reliable (8). If long distances are to be covered, and the less efficient but more powerful laser is required, then the Nd:YAG should be considered. If , however, the ISL is within a cluster or transverses a shorter distance, the GaAs or GaAlAs laser would probably be favored. Advances in diode arrays could alter this relationship. The estimate made earlier in this paper, 700 mW output for an array, would put arrays and the Nd:YAG at equivalent power output levels. Should this estimate hold true, the advantages inherent in GaAs and GaAlAs lasers would make them the optimum choice in most cases.

Optical Detector

There are two approaches to optical receivers that are enjoying popularity at this time. These are direct detectors (noncoherent) and heterodyne (coherent). Before discussing these two schemes, an overview of the generalities seems appropriate. (figure 5)

The basic elements of an optical detection system include a focusing lens and a photodetecting surface. For communication applications, an optical filter is included in order to limit the range of wavelengths admitted into the system. In this way, an optical bandwidth enters which, hopefully, contains

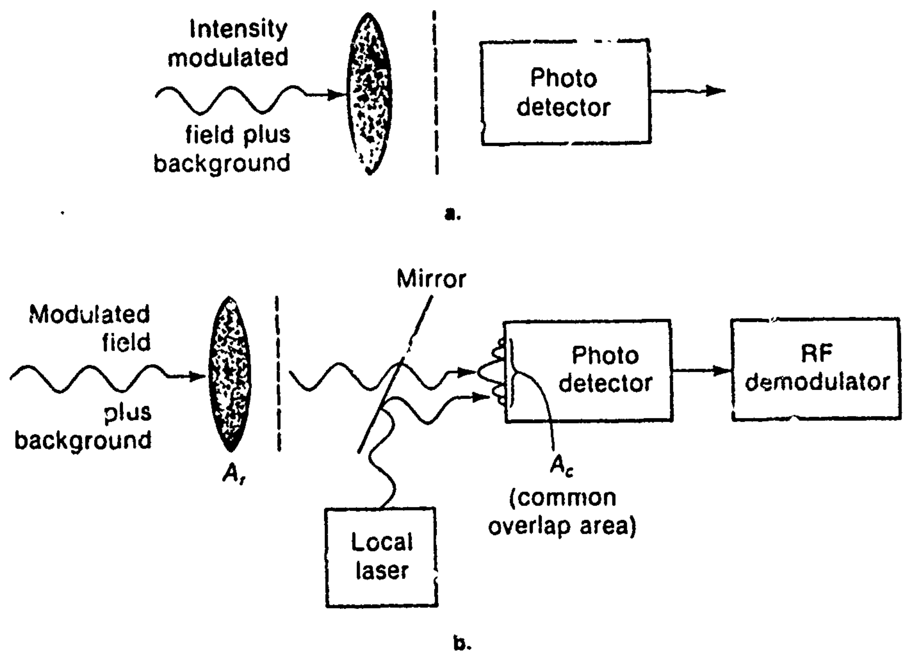

Figure 5. a. Direct (non-coherent) detection
b. Heterodyne (coherent) detection

the signal of interest and extemporaneous frequencies are filtered out.

The focusing lens concentrates the field onto a photodetecting surface, similar to the parabolic dish focusing the RF energy into the feed point. In RF systems the field is directly converted to an electronic signal. In optics, the frequencies are too high to be directly detected. This is where the photodetective surface comes into play. The surface responds quantum mechanically and a photoelectron flow (current) results from the radiation received. The amount of current is directly related to the instantaneous field intensity.(8)

In RF systems, the power received depended on the field of view of the antenna which depends primarily on the size of the antenna. In optical systems, things are a little different. The field of view in optics can be defined as the angles from which rays will be focused onto the photodetecting surface. This is independent of the area of the lens and will depend on the focal length and detector area rather than lens area.(8)

Not all of the power that reaches the photodetective surface is actually detected. The fraction of the power that is detected determines the efficiency of the detector. The efficiency will depend on the wavelength and material used on the detectors surface. Typical efficiencies range from 0.15 to 0.90 for frequencies in the visible range but decrease greatly at lower frequencies.(8)

An effective gain can be achieved during the detection process so that a single photoelectron emitted from the primary surface, due to the received energy, will produce numerous photoelectrons at the output. Various methods can be employed. Photomultiplier tubes or avalanche photodetectors (APD) are some of the possibilities. APDs have typically less gain (50-300 as compared to 10,000-1,000,000) but are smaller and lighter, important factors in satellite systems.(8)

In recent years, a great deal of interest has been generated in fiber optics. One by-product of this activity has been advances in APDs. AT&T Bell Laboratories has been studying advanced semiconductor structures. The technique has required careful material selection and the design of structures with optimal electron and hole ionization rates. This approach has been called bandgap engineering. One of the results of this approach has been the staircase APD. The performance of this particular APD is similar to a photomultiplier with virtually noise free multiplication at even high gains. Gains as high as 10^5 are claimed to be possible. (23)

The difference between what is commonly called a direct detection system (from the discussion above we know that it is not a true direct detection) and a heterodyne system has to do with whether a local oscillator is used or not. In a heterodyne system a local laser source is mixed with the received signal. This greatly increases the sensitivity of the receiver system. For example, in the 0.8 micrometer wavelength region (GaAs laser) a heterodyne system can have a 10-20 dB advantage over a direct detection system (22). The use of a local oscillator does have implications on the modulation scheme.

A direct detection system lends itself to intensity modulation. Whereas, phase modulation (PM), frequency modulation (FM), and amplitude modulation (AM) are possible in a heterodyne system. The heterodyne receiver can also be made to be less susceptible to background noise. (8) However, with the advent of bandgap engineering techniques, the margin between heterodyne and APD receivers has narrowed considerably in terms of performance.

All of the advantages of a heterodyne system are not without some sacrifice. The complexity of the system has increased. When the satellites go through the signal alignment process (acquisition) an additional element of the system must be tuned to the incoming signal. This will increase the acquisition time, even if only slightly. The most obvious advantage is that less powerful transmitters can be used. Heterodyne receivers permit the use of lower powered GaAs and GaAlAs lasers. These types of lasers offer reliability, compactness, direct modulation, and very rapid pulsing in the nanosecond range.(8)

Tracking and Acquisition

Because of the typically very narrow beams involved in optical communications, acquisition becomes a very important aspect. The times involved in acquisition, and the system itself, should be short enough and simple enough so that they do not dominate system performance. If the beamwidth involved is so narrow that acquisition is extremely difficult, then a broader beam, with more power output from the transmitter, should be considered.

There are two classes of illumination strategies and two classes of receiver structures applicable to lasers. These are parallel and sequential transmitter/receiver strategies. As in MMW ISL acquisition (discussed earlier) an initial orientation of the two satellites is made based on available ephemerides and telemetry data. This brings the systems into a range of uncertainty that the acquisition system is designed to work within. In a parallel receiver strategy, the uncertainty zone is covered by an array of receiver sensors. The outputs of these sensors are then analyzed simultaneously to determine which one received the signal. A sequential receiver would examine each sensor in a step by step manner or would step through a series of pointing angles. On the transmitter side, the parallel strategy involves illuminating the entire uncertainty area. In contrast, the sequential approach steers a beam through a determined series of angles. (24)

Frequency acquisition should be performed in conjunction with spatial acquisition. If a heterodyne receiver is used, a local oscillator will have to be tuned to the incoming laser source. Doppler shift of the frequency, due to relative motions, must be accounted for. The maximum doppler shift and rate of change anticipated in an ISL is +/- 10 GHz and 13 MHz/s. In addition, laser jitter must be tracked by the frequency tracking system. With a 10 mW transmitter power and a 1 milliradian pointing uncertainty, spatial and frequency acquisition should take about 1 to 10 seconds. (22)

During the initial orientation of two isolated satellites, a point-ahead factor enters into the problem. This is especially true when large distances are being transversed and the beamwidths involved are small. In the case of LES 8/9, discussed in detail in the MMW ISL chapter, the angle was negligible in comparison to the beamwidth involved. At their maximum separation of 75 degrees, the point-ahead angle was only 25 microradians (0.0014 degrees). The half-power beamwidth was about 1.2 degrees. Thus the point-ahead angle was well within the beamwidth. An approximate upper bound for the point-ahead angle is 105 microradians (0.006 degrees). This is assuming satellites in orbit 180 degrees apart . As long as the half-power beamwidth does not approach this size, the problem is inconsequential. These effects, as small as they are, can be a factor in optical ISLs (5). In a system proposed by Kaufmann and Jeromin (21), the beamwidth was 4 microradians. Clearly, a point-ahead angle would enter into the initial orientation of two satellites when beamwidths are this small.

In a general sense, a trade-off exists between the beamwidth and the cost of the tracking system. As the beamwidth is decreased, the precision required for tracking increases. This would increase the complexity as well as the cost of the tracking system. This increase in cost would be offset, at least partially, by the decrease in transmitter and receiver cost due to the high gain, and lower power requirement associated with a narrow beamwidth. As the beamwidth is decreased, a point of diminishing returns would occur. At this point the cost of tracking would overwhelm the benefits associated with a narrower beamwidth.

Proposed Systems

There is very little operational experience on ISLs and none on optical ISLs. Until an operational optical ISL is actually flight tested, there will be an element of doubt in any discussion of optical ISL systems. It is interesting, however, to examine some of the proposed systems and their parameters if only to get a rough idea of what the future holds.

Perhaps the most mature laser communication systems technology revolves around the Nd:YAG laser. This, to a great extent, is due to the USAF which made the decision to pursue this particular line of research early in it's program. For long range ISL applications, 1,000-40,000 km, Y.S. Lee and R.E. Eaves in a paper for the COMSAT Corporation (11) recommend the Nd:YAG and Nd:YA10 lasers (0.53 and 0.54 micrometers). They propose a duplex-link, pulse position modulation (PPM), direct detection system. These lasers would be frequency-doubled, mode-locked, and diode-array pumped.(11)

Table 8. Data rate, prime power, and weight estimates for a 50 degree (35,600 km), Nd:YAG ISL. Assuming PPM, BER=10^{-9}, mass includes power supply at 12 W/kg, laser efficiency = 0.24 percent.(11)

Laser Power (mW)	Data Rate (Mb/s)	Prime Power (W)	Weight (kg)
300	100	149.8	61.1
	200	156.4	64.1
	500	175.8	71.4
100	100	67.1	46.7
	200	73.9	51.3
	500	93.5	62.2
50	100	46.8	45.9
	200	53.7	52.3
	500	73.6	67.0

In applications of shorter distances, 1 km to 100 km, they proposed a single-mode semiconductor laser (GaAlAs) utilizing intensity modulation and direct detection (Si-APD). According to Lee and Eaves (11), a 20 km optical ISL can be designed using a 20 mW laser diode and a 10 cm aperture. This system could support a 500 MHz channel.

Table 9. Semiconductor Laser ISL (GaAlAs) Design Parameters

Source: GaAlAs laser diode
0.82 micrometers
Detector: Si-APD
Modulation: intensity modulation
direct detection
Laser Optical Power: 10 mW to 40 mW
Receive Optical Power: 0.1 mW
C/No: 130 dBHz
Harmonic Distortion: < -40 dB

It should not be concluded that single-mode semiconductor laser systems are limited to short distances. It should be possible to develop a long range (35,000 km) system utilizing advances in heterodyne receivers and power multiplying arrays.

Chan, Jeromin, and Kaufmann (22) examined the possible application of a heterodyne laser communications system using a GaAs laser (table 10). They concluded that, based on the then state-of-the-art in lasers and detectors, an efficient optical ISL would be possible with a few years of development. Their proposed design included some interesting features. The use of a heterodyne receiver makes it possible to use much less power on the transmitter side. They predict near-quantum-limit performance from this type of receiver. Frequency Shift Keying (FSK) was chosen because of the ease of modulating the frequency of the GaAs laser with variances in the injection current. Phase modulation was considered but would require external modulators or complex arrangements with injection locked lasers. For tracking and acquisition, a beacon from the receiving satellite would be continuously tracked by a beacon receiver at the transmitting satellite. This would permit telescope pointing of the transmitter. Identified as the most critical subsystem was the frequency (or phase) locking system for the local oscillator. The very week received signal (about 10 pW) could make matching the local oscillator to the received carrier difficult or complex. A summary of this proposed ISL design is contained in table 10.

Table 10. Strawman ISL design.

Data rate:	100 Mbps
Distance:	36,000 km
Aperture size:	12.5 cm
Beamwidth:	7 microradians
Modulation:	FSK
Photons RX per bit:	6
Transmitter:	25 mW GaAs
Receiver:	heterodyne
Optics loss TX/RX:	6.5 dB
Excess RX noise:	1 dB
Pointing loss:	1 dB
Link margin:	7 dB

Summary

This chapter should have shed some light on optical intersatellite links. Some of the major design issues peculiar to optical ISL technology were discussed. In a latter chapter, trade-offs and comparisons between optical and millimeter wave approaches will be discussed.

There are certain characteristics about optical ISLs and optical communications in general that make this approach to ISLs particularly attractive. The capacity (bandwidth) that an optical media can support is quite large. When this is viewed in light of the small antenna size (aperture) required, satellite applications become especially attractive.

CHAPTER V

TRADE-OFF ANALYSIS

In most endeavors there are trade-offs involved. A balance is struck between forces, pressures, or concerns. For example, when designing a building, a balance must be struck between aesthetics, functionality, safety, cost, etc. Communication systems are no exception.

In this chapter, some of the system trade-offs will be discussed. For the millimeter wave and optical ISL, comparisons between antenna diameter, transmitter power, carrier to noise ratio (receive power), and range will be examined.

Millimeter Wave System

The first parameter to discuss in an ISL is distance. For satellites in geostationary orbit, the distance between any two satellites is a function of the angle of separation. The relationship can be defined as follows :

$$R = 2\ (Ro + Ho)\ \sin\ (As/2)$$

where R is the range or distance, Ro is the radius of the earth (6,370 km), Ho is the altitude (35,800 km), and As is the angle of separation.

Table 11. Range between satellites given the angular separation.

Angular Separation (degrees)	Range (km)
5.00	3678
10.00	7350
15.00	11008
20.00	14645
25.00	18254
30.00	21828
35.00	25361
40.00	28845
45.00	32275
50.00	35643
55.00	38943
60.00	42170
65.00	45315
70.00	48375
75.00	51342
80.00	54212
85.00	56979
90.00	59637
95.00	62181
100.00	64608
105.00	66911
110.00	69087
115.00	71131
120.00	73040

The comparisons that follow are based on the equation below:

$$CNR = 0.71e9 \; Pt \; (f^2 \; d^4 \; / \; x^2 \; T \; B)$$

where CNR is the carrier to noise ratio, Pt is the transmission power (watts), f is the frequency (GHz), d is the antenna diameter (meters), x is the distance between satellites in terms of geostationary orbital distance ($x = D/35000$), T is the receiver noise temperature (degrees), B is the bandwidth (Hz). This equation is based on the assumption that the half power beamwidth is equal to the wavelength divided by the antenna diameter. Thus, the antenna efficiency factor is one. (8)

In any communications system relying on RF transmission, a major trade-off issue is the antenna size vs. transmission power. This is especially true for satellite systems where there are limits on power, weight, and size. To transmit over great distances, with limited power, a larger antenna (greater gain through directivity) could be used. On the other hand, the antenna size can be held constant and the power increased.

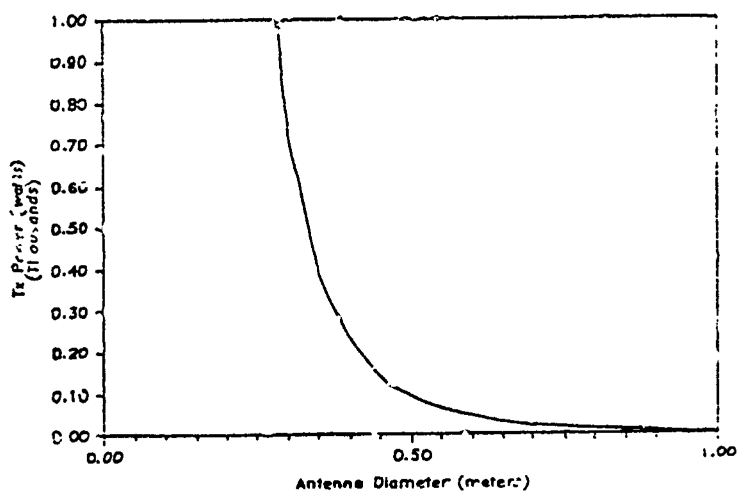

Figure 6. Antenna diameter vs. transmission power. CNR = 10, f = 60 GHz, x = 1 (distance of 35,000 km), T = 3000, B = 500e6 Hz.

In the above example the carrier to noise ratio at the receiver was held constant. An alternative to increasing the antenna size and/or power on the transmitter side is to increase the sensitivity of the receiver. In the following two figures the effect of varying the transmission power and antenna diameter are demonstrated.

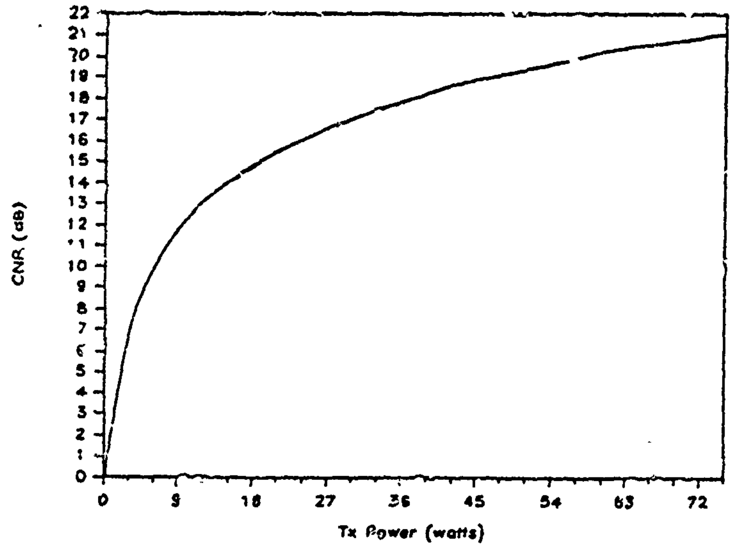

Figure 7. Transmission power (Pt) vs. CNR, where f=60 GHz, d=1m, x=1 (35,000 km range), T=3000, and B=500e6 Hz.

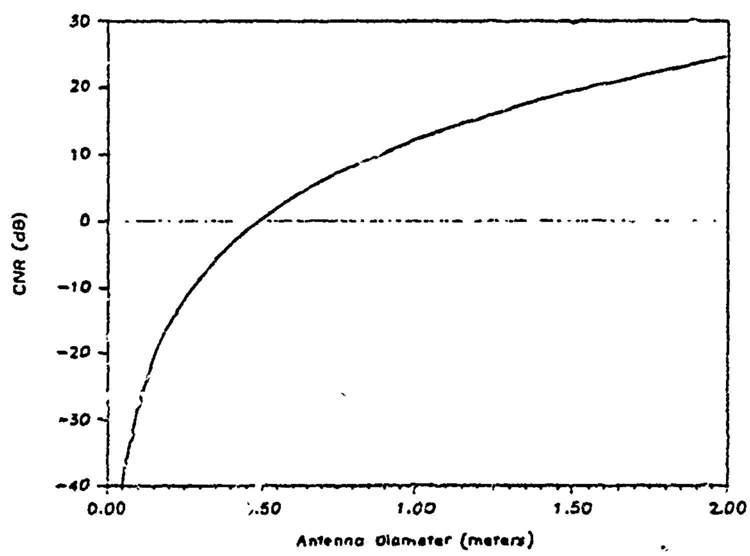

Figure 8. Antenna diameter vs. CNR, where Pt=10 W, f=60 GHz, x=1 (35,000 km range), T=3000, B=500e6 Hz.

Thus far we have manipulated the antenna size, the transmission power, and the carrier to noise ratio at the receiver. Through all of this the range has been held constant at 35,000 km. This value was chosen mainly due to the ease of manipulating the equation. In the next three figures the range is varied and the effect on antenna size, transmission power, and CNR are listed.

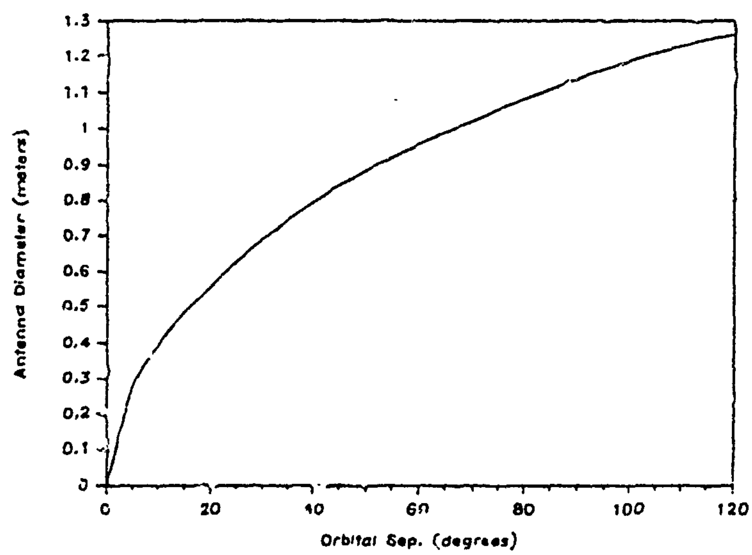

Figure 9. Range vs. antenna diameter, where CNR=10, Pt=10 watts, f=60 GHz, T=3000, B=500e6 Hz.

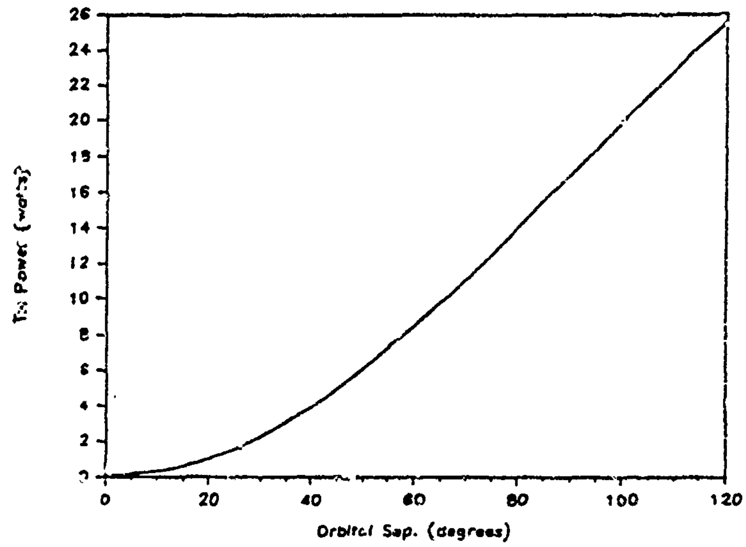

Figure 10. Range vs. transmission power (Pt), where CNR=10, f=60 GHz, d=1 meter, T=3000, B=500e6 Hz.

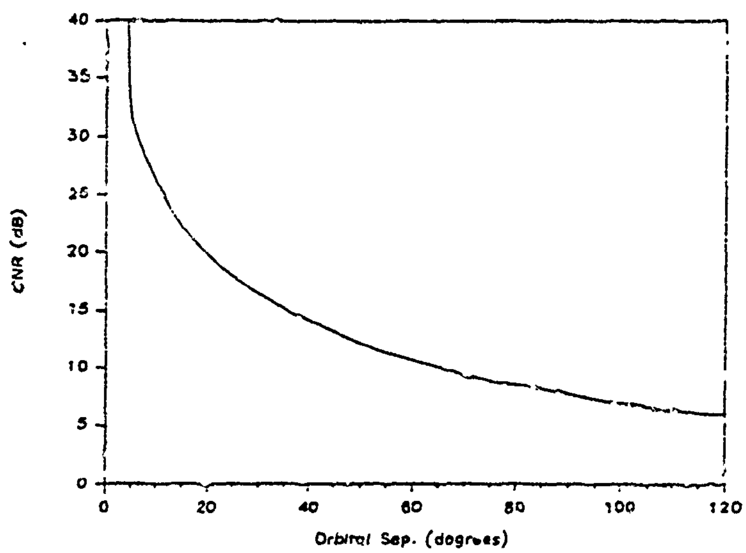

Figure 11. Range vs. CNR, where Pt=10 W, f=60 GHz, d=1 meter, T=3000, B=500e6 Hz.

It should be kept in mind that the results listed above, figures 6-11, are not real world values. As mentioned before, the efficiency factor of the antenna was assumed to be one. In addition, losses due to such things as pointing error, feed loss, and aging effects, were not accounted for.

Some conclusions can be drawn from the figures above, as well as from a casual observation of the equation itself. The antenna diameter has a tremendous effect on the CNR at the receiver. In the equation the antenna diameter is raised to the forth power. Of the variables in the equation, it is the most volatile in terms of it's effect on CNR. The frequency and the distance are both squared in the equation. They are the second most volatile. The other variables follow. In a practical sense, if all parameters in the equation could be manipulated with equal ease, varying the antenna diameter would be the most effective. However, in satellite systems, this is not always practical. An alternative is to raise the frequency.

Optical System

As mentioned in the previous chapter on optical ISLs, the received signal is not as dependent on antenna size for optical receivers as it is for RF receivers. The reception "area" in an optical system is the angular area from which light can be focused onto the detection surface. This makes specific comparisons rather complex. For our purposes we will deal with the power received as the power available over a collecting area equal to that of the cross sectional area of the antenna.

The equation used for the figures that follow is:

$$Pr=(Pt(dt\ dr)^2)/(L^2\ Z^2)$$

where Pr is the power received in watts, Pt is the transmit power in watts , dt and dr are the diameters of the transmit and receive antenna in meters, L is the wavelength in meters, and Z is the range or distance in meters. (8)

In the next two figures the transmit power is varied and the results on the other variables are viewed.

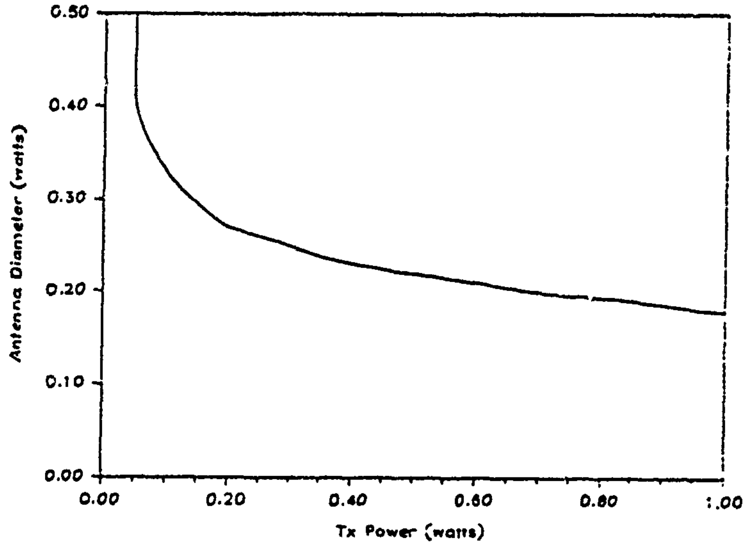

Figure 12. Transmit power vs. antenna diameter. Pr=1 microwatt (watts), L=1e-6 meters, Z = 35,000,000 meters.

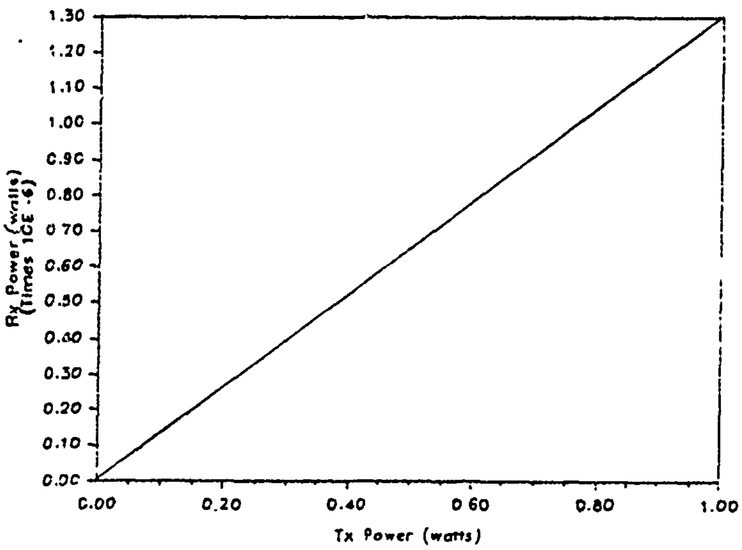

Figure 13. Transmit power vs. power received where dt and dr = .20 meters, Z=35,000,000 meters, L = 1e-6 meters.

As can be seen in figure 12, the antenna diameter involved in optical communications is quite small. This can be a major advantage.

If the antenna diameter is varied, it can have an appreciable effect on the link. In the next figure the antenna diameter is varied and its effect on the received power is presented.

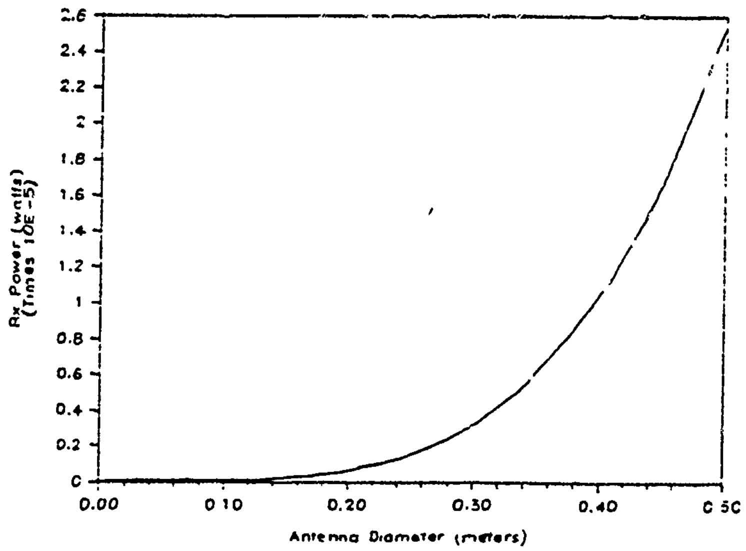

Figure 14. Antenna diameter vs. received power. Pt =0.5 watts, Z=35,000,000 meters, L=1e-6 meters.

In the next three figures the range between transmitter and receiver is varied and the effects on transmit power, power received, and antenna diameter are observed.

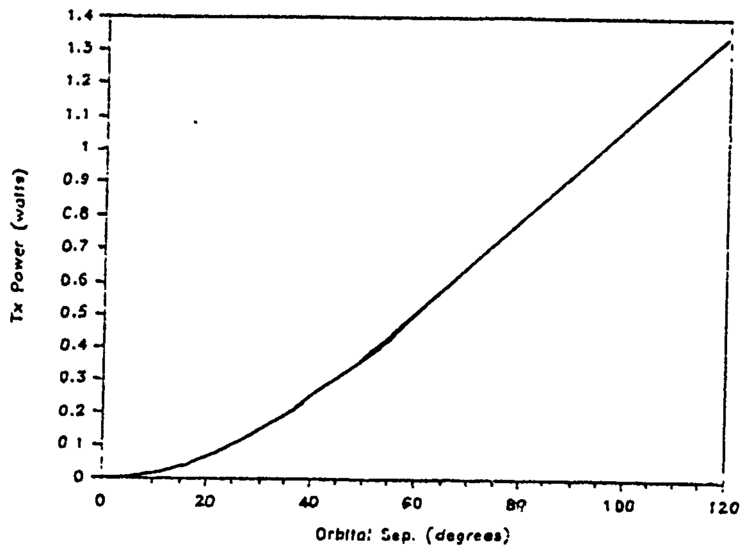

Figure 15. Range vs, transmit power. Pr=1e-6 watts, dt and dr = 0.20 meters, L=1e-6 meters.

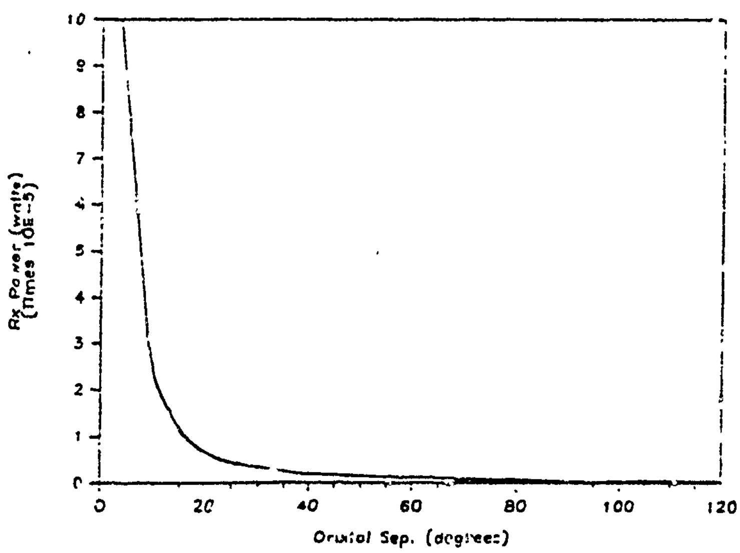

Figure 16. Range vs power received. Pt=0.5 watts, dt and dr = 0.20 meters, L = 1e-6 meters.

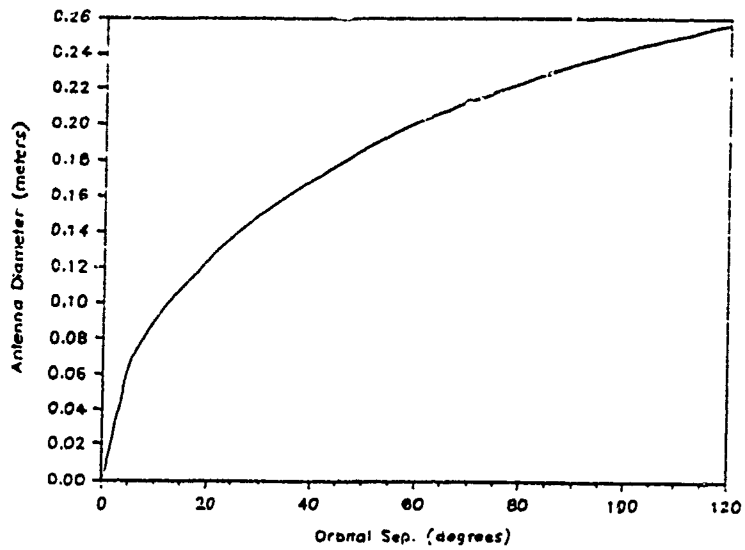

Figure 17. Range vs. antenna diameter. Pr=1e-6 watts, Pt=0.5 watts, and L=1e-6 meters.

After examining the equation and the figures above, it can again be concluded that the antenna size has a significant influence on the link. Again, the frequency (wavelength) also plays a major role. What is note worthy is that the antenna diameters and power levels involved in optical ISLs are much smaller than those for MMW ISLs. This is primarily due to the very short wavelengths involved in the optical region. In the equation there is an inverse relationship between wavelength and power received. The wavelength is also squared. Thus, as the wavelength gets smaller and smaller, it will have a great effect on the power received. The importance of size, weight, and power limits on-board a satellite has been emphasized already. Clearly, optical ISLs will be well suited in these areas.

Summary

In this chapter the trade-offs that may face a system designer were discussed for both optical and MMW ISLs. The trade-offs in MMW ISL and optical ISLs are very similar, although involving different technologies. The importance of antenna diameter and frequency were apparent. The relationship between power, frequency, and antenna diameter was examined.

When designing a satellite system, a plethora of factors must be balanced against one another. In this chapter, a few of the more important factors to telecommunications, have been reviewed.

CHAPTER VI

ISL APPLICATIONS

> Communications satellites have come to play a major role in international and several domestic networks. From the point of view of complete integration with global networks as well as more optimum utilization of orbital resources and investments, direct connectivity between satellites is the next major technological step.
>
> \- D.K. Sachdev

In this chapter the possible applications for ISL technology will be reviewed. The application of any technology is only limited by imagination. What is particularly exciting about ISL technology is that it strikes at the functional level of a satellite. When ISL technology is applied along with on-board satellite switching, the function of satellites leap from basic repeaters to switches in the sky. Such a network in the sky would literally encircle the globe with connectivity.

Geostationary ISLs

For the purposes of discussion, it is necessary to categorize the various geostationary

ISLs. Since the distance that an ISL must traverse has such an influence on the design, a convenient method is to categorize by distance.

Two broad categories are cluster ISLs and isolated ISLs. Cluster ISLs refer to ISLs between two satellites colocated within a single orbital area or cluster. Isolated ISLs refer to ISLs between satellites that are in distinctly different orbital slots. Isolated ISLs can be further divided into those between satellites with a separation of 3-40 degrees and those between satellites with a separation greater than 40 degrees.

Linking satellites that span over 40 degrees of separation can provide connectivity between communications networks on a transoceanic scale. Interconnection of satellites with separations between 3 and 40 degrees would provide a connection between earth stations pointing at different satellites. In both of these cases, the services that a single earth station can provide would be greatly expanded.(26)

The number of earth stations required for a global system could also be reduced. This would translate to dollar savings and greater profits for investors.(26)

Under optimum conditions, those being a fully interconnected global system, any one earth station could provide global coverage to it´s users without multiple up and down links. In addition, through the use of multiple spot beam antenna and ISLs, connectivity could be provided between two beam regions that would not be possible otherwise. (26)

ISLs can improve system performance and efficiency. The coverage area of two systems could be consolidated, eliminating unnecessary duplication. The look angles of earth stations could be optimized, improving system performance. ISLs would permit satellites to be located directly over earth stations rather than over a point half way between two earth stations.(27)

On a cultural level, global ISLs would permit international program exchange between broadcasting satellite networks. Some day we might be able to watch the evening news broadcast from Europe at the time of it´s origination. (27)

For military applications, ISL implementation would enhance the survivability and reliability of a satellite system. In a six satellite global system utilizing ISLs, double coverage to most user locations and a connectivity of two could be provided. In other words, the system could fully survive any single failure.(28)

Also important to the military is security. ISLs are relatively impervious to interception and ground based jamming. This was discussed in earlier chapters.

Interconnection of satellites within a cluster is another alternative. Colocation of satellites has been accomplished on a few occasions. COMSTAR D-1 and D-2 were colocated in order to augment each other due to their weakened batteries. Four INTELSAT IVA and V pairs have been colocated in order to transfer traffic.(11)

Mass and volume constraints placed on satellites the launch system have limited most satellites to very specific roles. With ISLs, the resources of several satellites could be pooled to achieve similar objectives. Modularity of satellites is also a possibility. For example, the functions of a single satellite could be dispersed among several satellites. This would effectively lift the weight and volume constraints. (26) If the methods that one of these satellites uses to accomplish it's mission becomes obsolete, that satellite could be replaced by a newer version. This can greatly increase the flexibility of the system as a whole.

An application of ISLs for tracking and telemetry is of particular interest to NASA. Without ISLs earth stations must be maintained around the world. This is an expensive proposition as well as being somewhat risky. There are no guarantees that a country which now welcomes NASAs presence, might someday change politically, and expel NASA. Currently being planned is NASAs Tracking and Data Acquisition System (TDAS) which will replace the Tracking and Data Relay Satellite System (TDRSS), mentioned in and earlier chapter. It is planned that TDAS will feature both MMW and laser ISLs. In terms of technology the MMW ISL is regarded as a medium risk while the laser ISL is regarded as a high risk. This risk estimate was based on implementation in the early 1990's. (29)

Although bordering on science fiction, it is conceivable that ISLs could be used for deep space missions. If a series of satellites were to be placed into a solar orbit identical to that of the earth, but trailing or leading the earth, our communications reach could be greatly extended. While there does not appear to be any pressing need for this kind of system at the moment, this may not be the case in a few decades.

Subgeostationary ISLs

As we enter into the space station era, communication links between geostationary satellites and manned vehicles will become very important. The importance of uninterrupted voice and data communications to the safety as well as success of future space missions can not be underestimated. To establish these links from ground would require numerous earth stations through out the globe. Whereas by using ISLs between low-orbit manned vehicles or satellites, and geostationary satellites integrated into a global network, only one earth station would be necessary. These links can be between the manned vehicle and the geostationary satellite directly or through a low-orbit relay satellite.

ISLs can also play a very important role in mobile satellite communication systems. One of the major difficulties to overcome in a mobile system like this is antenna size and the cost of the terminal equipment. A relatively low-powered system, with a small antenna, could transmit to a low-orbit satellite which would then retransmit up to a geostationary satellite for rebroadcast over it's high gain antenna. This type of approach would reduce the cost of the earth segment. The increased cost of tracking the low-orbit satellite would offset at least some of the savings.(28)

Slow Development

Why is it taking ISLs so long to gain real acceptance? It has been about ten years since the first ISL was demonstrated. If there were an appreciable economic advantage, wouldn't ISLs be farther developed, if not implemented by now? These questions can not be fully answered without a very extensive analysis. However, a general discussion seems appropriate.

There are a number of factors which tend to retard ISL implementation. First, there must be a need as well as an economic justification. For example, the amount of international traffic must be great enough to support the costs. For the military, while economics are important, other factors, such as survivability, are also important.

Second, the risk involved must be acceptable. Satellite systems must be design correctly the first time. As yet, we are unable to repair or modify satellites that are in geostationary orbit. Until the risks are lowered to an acceptable level, most organizations will be reluctant to invest themselves in this direction.

Third, development cycle times are increasing. While it is true that the time it takes to develop, design, build, and implement a system is dependent on the time and money put toward that effort, there appears to be a trend toward longer cycles. For example, the time between launches of different series of Intelsat satellites was only a year or two in the 1960's. More recently, the difference has been five and six years.

The areas where the implementation of ISLs look most promising are in manned space missions and in telemetry and tracking satellite systems. As mentioned earlier, NASA is already planning for this. In addition, the military, with it's special requirements for mobility and survivability, should prove to be an avenue for ISLs.

Summary

ISL technology could be very useful in future communication systems. It may alter communication satellite systems at even the functional level. To any communications satellite system it can offer greater survivability, reliability, as well as global connectivity. It's utility in future space missions during the space station era is appreciated by planners. Although regarded as somewhat risky today, in a few short years, the technology will have matured and practical implementations can begin.

CHAPTER VII

CONCLUSION

As we move into the information age, the pressures for viable telecommunications grow. Our lines of communication may become as important as rail and shipping were to the industrial revolution. The speed with which satellite technology has evolved attests to it's importance in our society. A few short decades ago, people marveled at simple reflective "balloons" in the sky. Today, a telephone call routed over a satellite network has become common place. We watch video pictures in our own homes, broadcast from some distant country over a satellite, and regard it as normal. By today's standards it is. People can now purchase their own private satellite receiver. Satellite communications has become a part of us and our society.

What are the next steps in the evolution of satellite communications? One of the technologies that will have an impact on future system designs is ISL technology. After reading this document, the reader should have gained an understanding of the major design issues involved in ISLs.

Millimeter Wave (MMW) ISL technology is of lower risk, at this point in time, than optical ISL technology. The LES 8/9 satellite mission flight tested the basic approach. The results show that ISLs are within reach. Design issues covered were frequency, antenna positioning, acquisition and tracking, antenna type, power amplification, and link analysis.

Development continues in the area of power amplification. Two method, solid-state IMPATT diodes and travelling-wave-tube (TWT), are currently in contention. At this point in time, the literature generally favors TWTs because of their greater power and bandwidth.

ISLs based on lasers tends to be regarded as a less mature technology than MMW ISL technology. However, it's potential is great. For requirements of higher data rates, optical ISLs are particularly suited due to the large bandwidths possible in the optical frequency range. The design issues covered were laser source, optical detector, and tracking and acquisition. Some proposed systems were also mentioned.

The laser sources that are currently enjoying "popularity" are Nd:YAG, GaAs, and GaAlAs. The U.S. Air Force chose the Nd:YAG as the source for it´s research thrust. With the development of very sensitive heterodyne receivers and/or the development of diode arrays, the GaAs and GaAlAs sources are alco viable.

The choice of optical detector revolves around direct (non-coherent) detection vs. heterodyne (coherent) detection. The heterodyne detector promises near quantum limit performance. Time will tell.

One of the characteristics of laser systems is the very narrow beamwidths. This is both a positive and negative aspect. It is positive in that it allows the concentration of power into a very narrow beam. But it´s disadvantage is that the problem of acquisition and tracking is compounded. Very precise methods of aligning the antenna of the two satellite are required.

Some basic trade-offs were analyzed. The relationship between power transmitted, power received, antenna size, distance, and frequency were examined. It was seen that the antenna diameter is particularly volatile.

Just some of the possible applications for ISLs were discussed. It remains to be seen where and in what context ISLs will be used. ISLs have the potential to provide the globe with a fully interconnected space based communications network. It could also impact mobile satellite communications by linking low-orbit relay satellites with geostationary satellites. Satellite resource sharing is also a possibility in a cluster scenario.

Summary

ISLs have unique design pressures. None appear to insurmountable. Their use can increase the potential of a communications satellite system tremendously. The much talked about "global village" may be that much closer.

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APPENDIX A

LIST OF ACRONYMS

AM - Amplitude Modulation

APD - Avalanche Photodetectors

AT&T - American Telegraph and Telephone

BCD - Biaxial Crosslink Drive

CNR - Carrier to Noise Ratio

COMSAT - Communications Satellite (Corporation)

DOD - Department of Defense

EHF - Extremely High Frequency

FCC - Federal Communications Commission

FM - Frequency Modulation

FSK - Frequency Shift Keying

IFRB - International Frequency Registration Board

IMPATT - Impact Avalanche Transit Time

INTELSAT - International Telecommunication Satellite Consortium

ISL - Intersatellite Link

ITU - International Telecommunications Union

LASERCOM - Laser Communications

LES - Lincoln Experimental Satellite

MMW - Millimeter Wave

NASA - National Aeronautics and Space Administration

PM - Phase Modulation

PPM - Pulse Position Modulation

RCA - Radio Corporation of America

RF - Radio Frequency

RTG - Radioisotope Thermoelectric Generator

TDAS - Tracking and Data Acquisition Satellite

TDRSS - Tracking and Data Relay Satellite System

TWT - Travelling-Wave-Tube

USAF - United States Air Force

WARC - World Administrative Radio Conference

APPENDIX B

TABLES FROM CHAPTER FIVE

The tables from which the graphs in chapter five were drawn, are included here. The figure associated with each specific graph has been referenced in the table description.

Table 12. Antenna diameter vs. transmission power. CNR = 10, f = 60 GHz, x = 1 (distance of 35,000 km), T = 3000, B = 500e6 Hz. (figure 6)

Antenna Diameter (m)	Power (watts)
0.05	9.39e05
0.10	58684.13
0.15	11592.15
0.20	3667.84
0.25	1502.35
0.30	724.51
0.35	391.07
0.40	229.24
0.45	143.11
0.50	93.90
0.55	64.13
0.60	45.28
0.65	32.87
0.70	24.44
0.75	18.55
0.80	14.33
0.85	11.24
0.90	8.94
0.95	7.20
1.00	5.87
1.05	4.83
1.10	4.01
1.15	3.35
1.20	2.83
1.25	2.40
1.30	2.05
1.35	1.77
1.40	1.53
1.45	1.33
1.50	1.16
1.55	1.02
1.60	0.90
1.65	0.79
1.70	0.70
1.75	0.62
1.80	0.56
1.85	0.50
1.90	0.45
1.95	0.40
2.00	0.37

Table 13. Transmission power (Pt) vs. CNR, where f=60 GHz, d=1m, x=1 (35,000 km range), T=3000, and B=500e6 Hz. (figure 7)

Pt (watts)	CNR	CNR dB
3.00	5.11	7.08
6.00	10.22	10.10
9.00	15.34	11.86
12.00	20.45	13.11
15.00	25.56	14.07
18.00	30.67	14.87
21.00	35.78	15.54
24.00	40.90	16.12
27.00	46.01	16.63
30.00	51.12	17.08
33.00	56.23	17.50
36.00	61.34	17.88
39.00	66.46	18.22
42.00	71.57	18.55
45.00	76.68	18.85
48.00	81.79	19.13
51.00	86.90	19.39
54.00	92.02	19.64
57.00	97.13	19.87
60.00	102.24	20.10
63.00	107.35	20.31
66.00	112.46	20.51
69.00	117.58	20.70
72.00	122.69	20.89
75.00	127.80	21.06

Table 14. Antenna diameter vs. CNR, where Pt=10 W, f=60 GHz, x=1 (35,000 km range), T=300C, B=500e6 Hz. (figure 8)

ant d (m)	CNR	CNR (dB)
0.05	1.065e-04	-39.72
0.10	0.001	-27.68
0.15	0.008	-20.64
0.20	0.027	-15.64
0.25	0.066	-11.76
0.30	0.138	-8.60
0.35	0.255	-5.92
0.40	0.436	-3.60
0.45	0.698	-1.55
0.50	1.065	0.27
0.55	1.559	1.92
0.60	2.208	3.44
0.65	3.041	4.83
0.70	4.091	6.11
0.75	5.391	7.31
0.80	6.979	8.43
0.85	8.894	9.49
0.90	11.179	10.48
0.95	13.879	11.42
1.00	17.040	12.31
1.05	20.712	13.16
1.10	24.948	13.97
1.15	29.803	14.74
1.20	35.334	15.48
1.25	41.601	16.19
1.30	48.667	16.87
1.35	56.598	17.52
1.40	65.460	18.15
1.45	75.325	18.76
1.50	86.265	19.35
1.55	98.354	19.92
1.60	111.673	20.47
1.65	126.300	21.01
1.70	142.319	21.53
1.75	159.816	22.03
1.80	178.879	22.52
1.85	199.598	23.00
1.90	222.066	23.46
1.95	246.381	23.91
2.00	272.639	24.35

Table 15. Range vs. antenna diameter, where CNR=10, Pt=10 watts, f=60 GHz, T=3000, B=500e6 Hz. (figure 9)

orbit sep	range (km)	d (meters)
5.00	3678	0.28
10.00	7350	0.40
15.00	11008	0.49
20.00	14645	0.56
25.00	18254	0.63
30.00	21828	0.69
35.00	25361	0.74
40.00	28845	0.79
45.00	32275	0.84
50.00	35643	0.88
55.00	38943	0.92
60.00	42170	0.96
65.00	45315	0.99
70.00	48375	1.02
75.00	51342	1.06
80.00	54212	1.08
85.00	56979	1.11
90.00	59637	1.14
95.00	62181	1.16
100.00	64608	1.18
105.00	66911	1.21
110.00	69087	1.22
115.00	71131	1.24
120.00	73040	1.26

Table 16. Range vs. transmission power (Pt), where CNR=10, f=60 GHz, d=1 meter, T=3000, B=500e6 Hz. (figure 10)

orbit sep	range	Pt (W)
5.00	3678	0.06
10.00	7350	0.25
15.00	11008	0.58
20.00	14645	1.02
25.00	18254	1.59
30.00	21828	2.28
35.00	25361	3.08
40.00	28845	3.98
45.00	32275	4.99
50.00	35643	6.08
55.00	38943	7.26
60.00	42170	8.51
65.00	45315	9.83
70.00	48375	11.21
75.00	51342	12.62
80.00	54212	14.07
85.00	56979	15.55
90.00	59637	17.03
95.00	62181	18.52
100.00	64608	19.99
105.00	66911	21.44
110.00	69087	22.86
115.00	71131	24.23
120.00	73040	25.55

Table 17. Range vs. CNR, where Pt=10 W, f=60 GHz, d=1 meter, T=3000, B=500e6 Hz. (figure 11)

range km	CNR	CNR (dB)
3678	1543.05	31.88
7350	386.39	25.87
11008	172.26	22.36
14645	97.32	19.88
18254	62.64	17.96
21828	43.81	16.41
25361	32.45	15.11
28845	25.08	13.99
32275	20.03	13.01
35643	16.43	12.15
38943	13.76	11.38
42170	11.73	10.69
45315	10.16	10.07
48375	8.91	9.50
51342	7.91	8.98
54212	7.10	8.51
56979	6.42	8.08
59637	5.86	7.68
62181	5.39	7.32
64608	5.00	6.99
66911	4.66	6.68
69087	4.37	6.40
71131	4.12	6.15
73040	3.91	5.92

Table 18. Transmit power vs. antenna diameter. Pr=1 microwatt (watts), L=1e-6 meters, Z = 35,000,000 meters. (figure 12)

Pt	ant. diameter
0.05	0.39
0.10	0.33
0.15	0.30
0.20	0.27
0.25	0.26
0.30	0.25
0.35	0.24
0.40	0.23
0.45	0.22
0.50	0.22
0.55	0.21
0.60	0.21
0.65	0.20
0.70	0.20
0.75	0.20
0.80	0.19
0.85	0.19
0.90	0.19
0.95	0.18
1.00	0.18

Table 19. Transmit power vs. power received where dt and dr = .20 meters, Z=35,000,000 meters, L = 1e-6 meters. (figure 13)

Pt	Pr
0.05	6.53e-08
0.10	1.30e-07
0.15	1.95e-07
0.20	2.61e-07
0.25	3.26e-07
0.30	3.91e-07
0.35	4.57e-07
0.40	5.22e-07
0.45	5.[illegible]7e-07
0.50	6.53e-07
0.55	7.18e-07
0.60	7.83e-07
0.65	8.48e-07
0.70	9.14e-07
0.75	9.79e-07
0.80	1.04e-06
0.85	1.11e-06
0.90	1.17e-06
0.95	1.24e-06
1.00	1.30e-06

Table 20. Antenna diameter vs. received power. Pt =0.5 watts, Z=35,000,000 meters, L=1e-6 meters. (figure 14)

ant. diameter	Pr
0.02	6.55e-11
0.04	1.04e-09
0.06	5.29e-09
0.08	1.67e-08
0.10	4.08e-08
0.12	8.46e-08
0.14	1.56e-07
0.16	2.67e-07
0.18	4.28e-07
0.20	6.53e-07
0.22	9.56e-07
0.24	1.35e-06
0.26	1.86e-06
0.28	2.50e-06
0.30	3.30e-06
0.32	4.27e-06
0.34	5.45e-06
0.36	6.85e-06
0.38	8.51e-06
0.40	1.04e-05
0.42	1.27e-05
0.44	1.52e-05
0.46	1.82e-05
0.48	2.16e-05
0.50	2.55e-05

Table 21. Range vs, transmit power. Pr=1e-6 watts, dt and dr = 0.20 meters, L=1e-6 meters. (figure 15)

orbit sep	range km	Pt
5.00	3678	5.98e-03
10.00	7350	0.02
15.00	11008	0.04
20.00	14645	0.07
25.00	18254	0.11
30.00	21828	0.15
35.00	25361	0.20
40.00	28845	0.26
45.00	32275	0.31
50.00	35643	0.37
55.00	38943	0.44
60.00	42170	0.51
65.00	45315	0.58
70.00	48375	0.65
75.00	51342	0.72
80.00	54212	0.79
85.00	56979	0.87
90.00	59637	0.94
95.00	62181	1.01
100.00	64608	1.08
105.00	66911	1.15
110.00	69087	1.22
115.00	71131	1.28
120.00	73040	1.35

Table 22. Range vs power received. Pt=0.5 watts, dt and dr = 0.20 meters, L = 1e-6 meters. (figure 16)

orbit sep	range km	Pr
5.00	3678	8.35e-05
10.00	7350	2.30e-05
15.00	11008	1.09e-05
20.00	14645	6.53e-06
25.00	18254	4.38e-06
30.00	21828	3.17e-06
35.00	25361	2.42e-06
40.00	28845	1.92e-06
45.00	32275	1.57e-06
50.00	35643	1.31e-06
55.00	38943	1.12e-06
60.00	42170	9.76e-07
65.00	45315	8.59e-07
70.00	48375	7.65e-07
75.00	51342	6.88e-07
80.00	54212	6.25e-07
85.00	56979	5.72e-07
90.00	59637	5.28e-07
95.00	62181	4.91e-07
100.00	64608	4.59e-07
105.00	66911	4.31e-07
110.00	69087	4.08e-07
115.00	71131	3.87e-07
120.00	73040	3.70e-07

Table 23. Range vs. antenna diameter. Pr=1e-6 watts, Pt=0.5 watts, and L=1e-6 meters. (figure 17)

orbit sep	range km	ant. diameter
5.00	3678	0.066
10.00	7350	0.091
15.00	11008	0.109
20.00	14645	0.125
25.00	18254	0.138
30.00	21828	0.149
35.00	25361	0.160
40.00	28845	0.169
45.00	32275	0.178
50.00	35643	0.186
55.00	38943	0.194
60.00	42170	0.201
65.00	45315	0.207
70.00	48375	0.213
75.00	51342	0.219
80.00	54212	0.224
85.00	56979	0.229
90.00	59637	0.234
95.00	62181	0.238
100.00	64608	0.242
105.00	66911	0.246
110.00	69087	0.250
115.00	71131	0.253
120.00	73040	0.256