

Key technology trends – Satellite systems

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This paper is based on material extracted from the WTEC Panel Report Global Satellite Communications Technology and Systems, December 1998. It presents an overview of key technology trends in communications satellites in the last few years. After the introduction which deals with such issues as the transformation of the one-at-a-time approach for building satellites to a production-oriented one, there follows a discussion of critical technologies for large geosynchronous earth orbit (GEO) satellites with power systems growing to 20 kW and more. Satellite antenna technology, one of the most critical areas in measuring progress, is next reviewed, including large reflector antennas, phased arrays and optical beam formers. This is followed by a discussion of onboard processing (analog and digital), progress in satellite traveling wave tubes, solid state power amplifiers and optical satellite technologies including intersatellite links (ISLs). Last some pertinent satellite bus issues (electric propulsion, thermal control and attitude control) are reviewed. Small and mini-satellites are discussed, but not treated in great detail as much of their technology is derived from that of GEO satellites.

Keywords: Satellite communications, Communications satellites, Satellite technology overview

1. Introduction

This paper reviews the status of technologies for communications satellite systems space segments. It is largely based on material from Chapter 3 of the WTEC Panel Report Global Satellite Communications Technology and Systems, December 1998 [1]. The paper highlights changes that have taken place since the previous study conducted in 1992/1993 [2] and emphasizes developments that are both new and important.

In 1992 the National Aeronautics and Space Administration (NASA) and the National Science Foundation (NSF) commissioned a panel of US satellite engineers and scientists to study international satellite R&D projects in order to evaluate the long-term presence of the United States in this industry [2]. In the five years since that study, the satellite communications industry has become an even larger industry than most had predicted, increasing from \$11 billion in 1992 to \$20 billion in 1996. Far from being supplanted by fiber optics or other communications networks as some suggested would happen, satellite systems and services (based on improved technologies and architectures) are expanding as more countries establish communications satellite system capabilities. Because of the continued technological advancements of the industry and its worldwide growth, NASA and NSF commissioned a panel in 1997 to update the earlier study and also extend the scope to include additional countries. This study also included policy and regulatory issues that are becoming increasingly important to this global industry.

In the past in any discussion of satellite communications there was a tendency to emphasize satellites. More recently the importance of satellite terminals both in the economics and user acceptance of systems is being recognized in industry. Designers of systems have exercised the tradeoffs between satellite and earth terminals in a conscious attempt to achieve high system capacity while realizing a small and affordable terminal.

Some designs for mobile satellite systems have reduced the orbit altitude and employed a larger than familiar number of satellites to achieve continuous global coverage. The reduced altitude reduces the propagation delay and the (spreading) path loss, which can be traded for lower transmit radiated power. Although this design approach leads to smaller satellites, innovations have nevertheless been introduced, such as use of Global Positioning System (GPS) satellite receivers on satellites for autonomous station keeping; multiple crosslink (intersatellite link) antennas; phased array antennas for up and downlinks; and onboard baseband processing.

The assembly of satellites used to proceed on the basis of 'one of a kind-one at a time'. Some manufacturers (notably for the Iridium and Globalstar satellites) have adopted techniques similar to those used by the automobile industry by setting up assembly lines using parts and subsystems delivered from manufacturers located all over the globe and generally reducing the extensive environmental testing conducted on satellites prior to launch. Manufacturers of geosynchronous earth orbit (GEO) satellites have also streamlined the assembly by concentrating on standard buses varying the communications packages carried by the standard bus.

While low and medium orbit communication satellite constellations have rightly attracted much attention in the past few years, geostationary orbit communications satellites systems have continue to thrive and grow, both in numbers and in the capacity of the individual satellites. The ability to keep coverage fixed and provide high capacity over long distances offers the possibility of a gradual market entry, i.e., market development. This lowers the risk and is thus desired by the financial community. In any case, there is continued development of ever larger buses to support ever increasing antenna size and complexity, large numbers of transponders, and other dimensions in sophistication and complexity, all of which will be discussed herein and in companion papers in this issue [3-5].

The trend in GEO satellites is as always toward increased power and an increased number of transponders. Satellites with numerous C- and Ku-band transponders and antenna beams are commonplace. These increases have not resulted in a proportionate scaling of satellite mass, since the use of shaped reflector antennas eliminates the need for considerable microwave plumbing and the use of lighter structures has helped contain satellite mass. Nevertheless, GEO satellites are becoming heavier and launch capability is increas-

ing to accommodate the additional features of modern satellites. Increased on-board power is driven by the desire to radiate more rf power towards the ground terminal thereby decreasing the ground terminal size and cost, appealing features for end-consumer equipment. Figure 1 provides a comparison between GEO satellites of the 1970s, 1980s and early 1990s, as well as buses now in development in terms of mass and power. The figure shows on a related scale how the increases in power have allowed a steady reduction in terminal sizes. Given that a ground terminal size on the order of 30 cm has been attained, further increases in satellite power may be viewed as making larger capacities possible using these small terminals, or may be used to add other features such as additional frequency bands or crosslinks to other satellites (as opposed to further reducing terminal sizes).

This paper begins with a discussion of critical technologies of large GEO satellites where the primary power system is growing rapidly towards 20 kW and more. Satellite antennas are discussed in some detail since this is one of the most critical areas in measuring communications progress. This is followed by a discussion of onboard processing, progress in satellite traveling wave tubes and solid state power amplifiers, optical ISLs and some satellite bus issues (electric propulsion, thermal control and attitude control). Larger satellite antennas imply narrower beams which in turn leads to a need for tighter attitude control. In all cases emphasis is placed on what was learned during the above mentioned study.

Small and mini-satellites derive much of their technology from that of GEO satellites and therefore are not treated in detail. The major aspect of these satellites is the process adjustments made to transform the one-at-a-time, hand-made approach taking three to four years, to a more streamlined, production oriented approach for producing satellites.

2. Large GEO satellites

2.1. Size trends

During the past five years, there has been a renewed emphasis on providing satellite-based services to consumers. The acceptance of these services is determined to a great degree by cost to the consumer, including the price to the consumer of the equipment as well as monthly service charges. The price of consumer electronics benefits from competition and the cost sav-

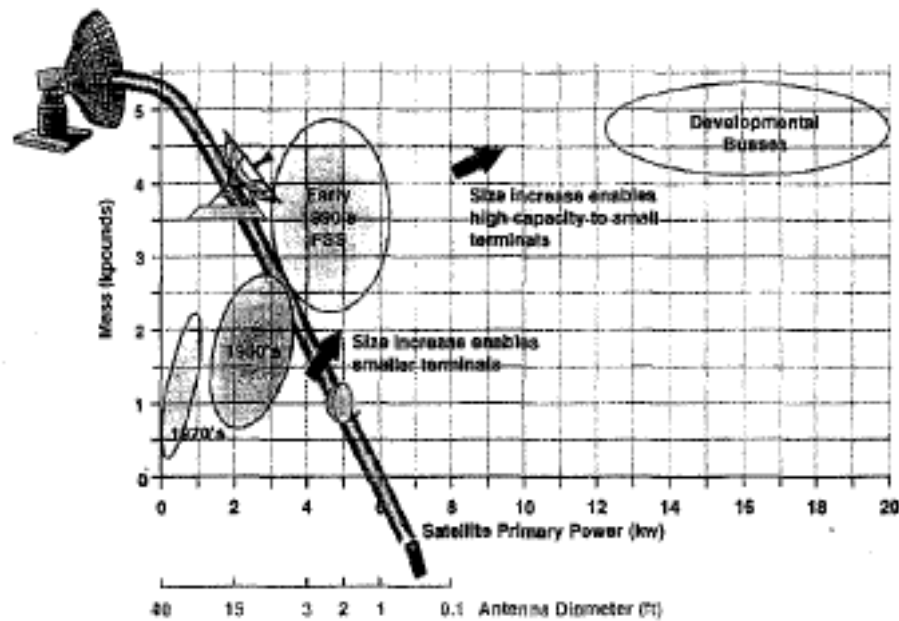


Fig. 1. Satellite power/mass and terminal antenna size trends.

ings associated with volume manufacturing and distribution. This is vividly demonstrated by the rapid decrease in the price of direct broadcasting satellites (DBS) home equipment. The size of the home terminals is also a critical item. Home owners do not want large, obtrusive satellite dishes attached to their roof or the side of their home. The same is true for the mobile phone terminal. Customers are used to the size and weight of a typical cellular phone and are hesitant to use a satellite mobile phone that is considerably heavier and larger than the shirt pocket sized terrestrial cellular phone. The power of the signal from the satellite is a critically important factor in determining the cost of the ground equipment or terminals. The more power from the satellite, the less the size and cost of the terminal. The size of the antennas and the cost of the amplifiers decrease as the power from the satellite increases.

Business customers benefit from this increased power for the same reasons, in GEO-based communications satellite systems providing business services. As these costs are driven down, new applications for satellite services emerge. An interesting example of this is the presence of 55 cm satellite antennas at gas station pumps, which are used for credit card transactions. Of course, the multitude of recently proposed mobile and high bandwidth data services are also dependent on the existence of low cost terminal equipment.

The need for more power and bandwidth from commercial satellites is obvious to all the satellite manufac-

turers. Typically, you would expect that increasing the power and bandwidth from the satellite would require a larger, and thus heavier, satellite. However, increasing the weight of the satellite adds to the cost of the launch. Indeed, the maximum weight of the satellites is often capped by the lift capability of the launch system. Thus the challenge of the satellite manufacturers is to design and deliver a satellite with increased power, without increasing its cost and mass. Needless to say, this higher power requirement has led to heavier GEO satellites and the launch providers have responded to this by increasing the lift capability of their rockets.

Thus today the increased demand for power is the dominant factor in driving the development and utilization of new GEO satellite technology, especially to meet these weight and cost constraints. Bandwidth per satellite has been increasing as combined C- and Ku-band satellites become more common. The need for more bandwidth is especially evident for the new data applications, which are expected to be met with Ka-band and possibly V-band satellites. Here again, more total power is needed to meet power per channel (or per Hz) requirements.

Other factors driving the increased size and weight of the satellite are the needs for larger antennas, on-board processing electronics, and intersatellite links. Considerable technology development is directed towards the reduction of this weight and the size of the satellite. For large GEO satellites the rocket fairing is

typically 4 m in diameter, and the satellite has to fit into that cross section. Examples of new technology to minimize the size and weight and to increase the power of GEO satellites, are numerous. We are seeing the insertion of new lightweight composite materials into the structural composition of the satellite, the use of more efficient propulsion systems and fuels to insert the satellite into its final orbit and for station keeping, the use of arc jets and ion engines to increase the efficiency of the fuel that is used for station keeping, the reduction in the number of feed horns and their associated wave guides by using shaped reflector antennas, the use of higher efficiency power amplifiers (TWTA & SSPA) the use of optical fiber to replace copper wires for the busing of signals onboard the satellite, the use of higher efficiency solar cells such as 'black' Silicon, GaAs (on Ge) and multiple junction, multiple material cascade cells to replace the workhorse Si

cells of the past, the welding of solar cells onto the array to decrease costs and to eliminate heavy solder, the use of light structures for solar panels, the use of unfurlable solar arrays, the use of more efficient heat exchangers, and the use of more efficient high pressure Ni-H₂ batteries. Figure 2 illustrates how the weight of the typical GEO satellite has increased over the past 30 years.

2.2. Power subsystem

As mentioned previously, the demand for increased microwave power from the satellite is probably the most important factor in driving the insertion of new technology into modern GEO satellites. Higher power at the customers' antenna translates into lower cost equipment and the availability of new services and thus the need for the manufacture of more satellites and their associated launches. The demand for more power from satellites is driving the development of considerable new technology, with the requirement that this new technology does not add to the cost of the satellite or its weight, which translates into increased launch costs. Figure 3 illustrates the trend of the increasing power capability of GEO satellites over the past 35 years.

The power subsystem is composed of the solar array (solar cells on the supporting structure including pointing devices), batteries, and the power condition-

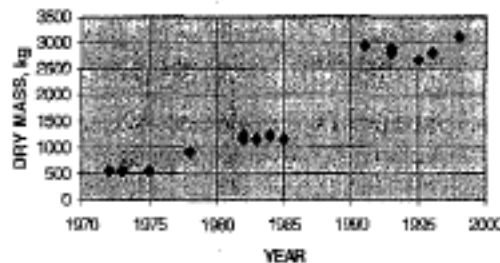


Fig. 2. Spacecraft mass (kg) vs. time (year).

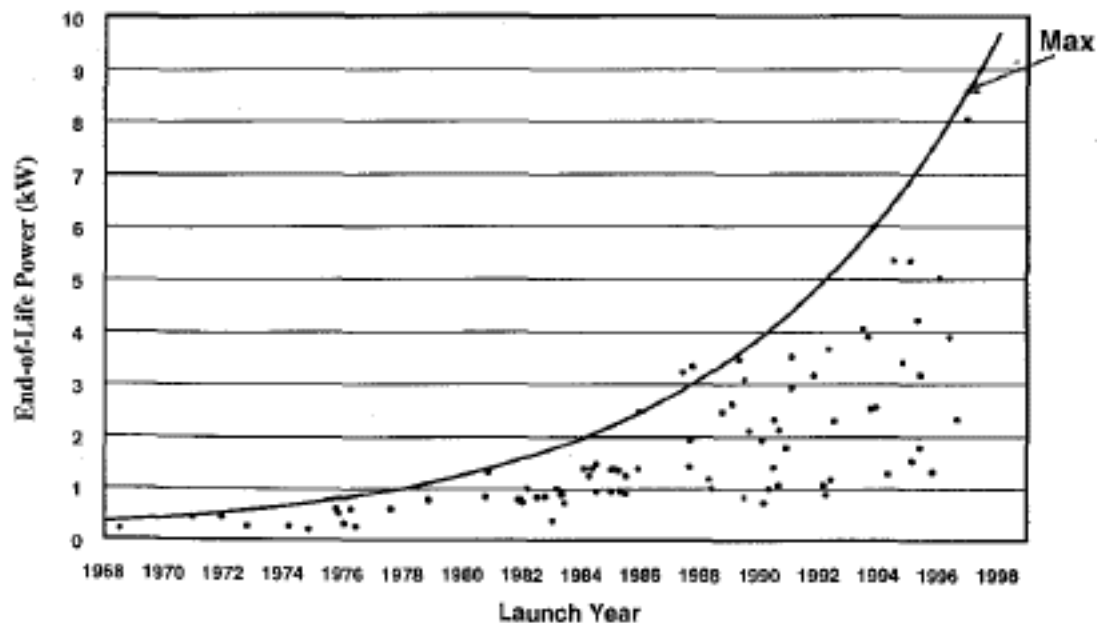


Fig. 3. Spacecraft power/time.

Table 1
Solar cell efficiency vs. time

Year	Organization	Efficiency (%)	Material	Comments
1962	ATT Bell Labs	8-10	Si	Basic design, trendsetter
1970	COMSAT Labs	13.5	Si	Violet cell
1973	COMSAT Labs	15.5	Si	Non reflecting cell (black cell)
1976	COMSAT Labs	16.1	Si	Black cell, sawtooth cover slide
1993	Sharp	17-18	Si	Black cell, improved materials
1997	Spectrolab and Techstar	25.5	GaAs/Ge	Dual junction
2000	Spectrolab and Techstar	35	III-V comp'ds	Cascade cells

ing electronics. Considerable progress has been made in the last five years in particular in the efficiency of solar cells. These are an important part of the power system and improvements in efficiency are key to the ability of satellites to deliver higher power. The efficiency of solar cell technology over the years is summarized in Table 1.

In the mid 1990s, Sharp started delivering a high efficiency silicon cell, commonly referred to as the 'black silicon cell' because of its appearance. This cell has rapidly become widely used for communications satellites with its efficiency of 17-18%. This advance was followed quickly by the availability of GaAs cells, with an efficiency of 18-19%. While it has long been known that GaAs has an intrinsically higher efficiency than silicon, the difficulty in fabricating GaAs cells that are competitive in cost to silicon has prevented large scale application in satellites. This changed with the development of techniques to grow and dope layers of GaAs that have been epitaxially grown on germanium substrates. Spectrolab (a division of Hughes) and the Applied Solar Energy Division of Techstar are two US-based companies that are primary suppliers of these cells. The shortage of germanium, since it is widely used in the fabrication of fiber for the communications industry, has led to shortages of these cells. As these cells become available they have been used on the solar arrays of many recently delivered satellites. Arrays have been constructed that contain both Si cell panels and GaAs/Ge cell panels due to this shortage, heritage designs and cost tradeoffs. These GaAs/Ge cells cost approximately 4-5 times more than Si cells. In addition, they are heavier and more fragile than the Si cells.

In addition to efficiency, resistance to radiation is another parameter involved in the design of the solar arrays. Since the GaAs/Ge cells are more resistant to the damage caused by high energy particles from the sun than is Si, it is not necessary to include as many additional cells to meet end-of-life (EOL) power re-

quirements. The radiation damage is cumulative and causes the power output of Si cells on GEO satellites to decrease ~10-15% over their lifetime, requiring additional cells to achieve EOL power requirements. GaAs/Ge requires considerably fewer cells to compensate for this loss of power. The success of the epitaxial GaAs on Ge process has led to the extension of this process to the design and fabrication of multi junction, or cascade, cells, which are also made by Spectrolab and Techstar. These cells are composed of several layers of III-V compound materials, such as GaAs, GaInP, GaInAsP and GaSb grown epitaxially on Ge. These cells are also quite resistant to radiation, and cells with an efficiency of ~26% have been delivered to customers for evaluation. With additional R&D, it is anticipated that cells having an efficiency of 35% will be developed in the near future. Since these cells are made by a process that is quite similar to that used to manufacture the GaAs/Ge cells, it is expected that these exotic cells will not be that much more expensive. If progress continues at the present pace, these high efficiency, cascade cells could be the dominant source of power for satellites in the near future.

During the past two years, several GEO satellites have experienced an unusual degradation in the power output of their solar arrays, leading to premature decrease in the lifetime in orbit. In addition, the launch dates of several satellites have been delayed until this problem is eliminated. It appears that this problem is not directly attributable to the solar cells, but rather to the normally mundane cover glasses that protect the cells from damage. One explanation is that the increase from ~35 V to 70-100 V on the power bus enables some of the protective glass covering the solar cells to charge up to high voltage, due to high energy solar particle bombardment. Subsequent discharge of this high voltage charge on the cover glass destroys devices and interconnects. Another explanation is that the transparency of a new coating on the cover glass degrades from ultraviolet light. This major problem is an exam-

ple of the problems that can be encountered when technological changes are made on-board a satellite. Even subtle modifications need to be done carefully.

Another promising solar array technology is the use of concentrators to focus the light down onto the GaAs cells. AEC-Able Engineering Co, Inc. of Goleta, CA is working on parabolic reflectors that gather 7–8 times the light that would normally fall on a cell. These reflectors would also shield the cells against the high energy particles that degrade the cells. Such a technology would offer the promise of reducing the number of cells and the weight and thus the cost of the solar array.

The design of the solar array itself is also evolving to improve the total power handling capability of the satellites, as well as reducing the weight and volume of the array. Large area arrays have been designed at Mitsubishi and Loral that involve the addition of panels that fold out from the main array. Lockheed Martin has designed a lightweight 'pleated shade'-like structures that fold out like an accordion on a boom. These structures are light in weight, take up little space and offer considerable promise as an array structure. TRW is building flexible solar arrays on blanket-like structures that also offer the promise of reducing the weight and volume of high powered arrays.

Batteries are the next important component of the power system. At the present time, high pressure Ni-H₂ cells are widely used for GEO satellites. However, as the need for more power onboard satellites increases, then so does the requirement for increased power storage capability, which is met by batteries. Since the weight of the batteries typically scales with the power storage capability, we are going to see an increased percentage of the total weight composed of batteries, unless we have more efficient batteries. This is a critical technology that needs R&D attention. Lithium-ion is a system that offers possible solutions to this critical battery technology problem. The ability to support the numerous charge/deep-discharge cycles during the lifetime of a satellite has to be demonstrated for this system. Hopefully the experience gained from the expected broad consumer use of Li-ion batteries (for such applications as laptop computers and cellular phones) will help solve some of the problems facing the system. While some Li-ion batteries are being used for short lifetime government satellites, much R&D still needs to be done on this high storage power density system before they will be used on commercial, long lived GEO satellites. The experimental STENTOR satellite of CNES is designed to use Li-ion batteries.

Flywheel storage of energy is a possible substitute for batteries as improved bearings and stronger, lightweight materials are developed.

3. Antennas

3.1. Overview

The key trends in spacecraft antenna technology are toward larger effective apertures, significantly higher numbers of beams, and integrating computationally-intensive beam forming and switching activities with other onboard processing functions. These trends are an integral part of universal efforts to raise spacecraft effective radiated powers (ERP)s, make communications payloads smarter and more flexible, and make earth terminals smaller and cheaper. Table 2 provides a good indication of the near-term state of the art, illustrating the antenna systems that a representative sample of commercial Ka-band operators plan to fly in the 2000–2005 time frame. Many manufacturers offer competing proprietary technologies to build these antennas, and there is no clear world leader. Details of ongoing research and development efforts are generally proprietary. The situation has changed significantly from when large government research programs drove spacecraft antenna technology and quantitative information about the state of the art was reasonably available.

A major change noted since the 1992/1993 study is the improvement in the mechanical technology and manufacturing processes associated with spacecraft antennas. For example, while the ISL and gateway antennas (Fig. 4) manufactured by COMDEV for the Iridium spacecraft represent state-of-the-art electromagnetics, their mechanical characteristics are also impressive. These antennas provide excellent pointing and tracking characteristics while coming off an assembly line on a one-set per week basis. This is a significant change from spacecraft antennas being individually hand-assembled by highly skilled engineers and technicians.

3.2. Large reflector antennas

There are a number of competing technologies worldwide for building large reflectors. The Lockheed Martin ACeS (Asia Cellular Satellite) spacecraft typify the current state of the art with two twelve-meter antennas and 140 total beams per satellite (see Fig. 5) [6].

Table 2
 Characteristics of planned commercial Ka-band communications systems

System	Astrolink	Cyberstar	Euroskyway	East	West	Spaceway	Celestri	Teledesic
Sat orbit	GEO	GEO	GEO	GEO	GEO/MEO	GEO	LEO	LEO
Number	5	3	5		12.9	20	63	288
Coverage*	Pop. Centers	N.A. Eur., Asia	Eur., Afr., midEst.	Eur., Afr.	Eur., Afr., midEst	Pop. Centers	Global	Global
Beamwidth/spot		0.800	~100	~100	0.600	~100		
No. Beams	96	72	32		64	24	432u, 260dn	64
Type Sat Antenna	Horn fed	Horn fed	Horn fed	Horn fed	Horn fed	Horn fed	Array	Array
Market	Multimedia	Multimedia	Multimedia	Infrastructure	Multimedia	Infrastructure	Infrastructure	Infrastructure
On Board Proc.	Full	Baseband	Baseband	Baseband		Baseband	Full	Full
Through-put	7.7 Gb/s	4.9 Gb/s			6Gb/s	4.4 Gb/s	1.8Gb/s	13.3 Gb/s
ISL	V-band	Potentially V		V-band	Optical	V-band	6 optical	V-band
Terminals	Fixed	Fixed	Fixed	Fixed, mobile	Fixed	0.66 m		Fixed
Smallest size	Not given	0.7 m		0.7 m, RH	0.7 m typ.			0.15

*Source: Third Ka-band Utilization Conference.

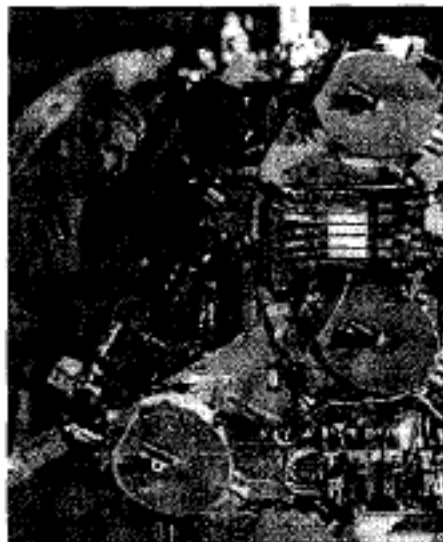


Fig. 4. Iridium satellite gateway antennas (Iridium 1997).



Fig. 5. Prototype Lockheed Martin ACeS antenna (Mecham 1997).

The ACeS system will offer GEO-based service to hand-held terminals at L-band and S-band.

While the previous study emphasized efforts (Russian programs in particular) to orbit ever larger antennas, the decreasing coverage areas associated with larger apertures and smaller beamwidths today seem to obviate the commercial need for reflector diameters significantly larger than 12 to 15 m. Accordingly there is less interest now in large inflatable antennas. In the future we anticipate that competition will be in minimizing mass, surface deviation, thermal distortion, and cost, and maximizing ease of deployment. Thus the French STENTOR spacecraft will carry what is described as an ultra-lightweight 2.4 m reflector.

In 1992 two large-reflector technologies were being developed in Japan that differed from other approaches. One, using robotic assembly in space, has been discontinued. The other, Toshiba's modular approach, will be tested with the launch of the ETS VIII spacecraft.

Toshiba's design is based on hexagonal cross-section modules. Nineteen modules combine to make the ETS-VIII 15 m diameter reflector with a total mass of less than 170 kg and 2.4 mm rms surface deviation.

3.3. Phased arrays

Phased array antennas are a critical technology area where cost breakthroughs are needed. Both direct radiating arrays and phased array feeds for reflectors are attractive for multibeam spacecraft antennas that must route traffic dynamically. All major spacecraft and antenna manufacturers seem to be working on phased

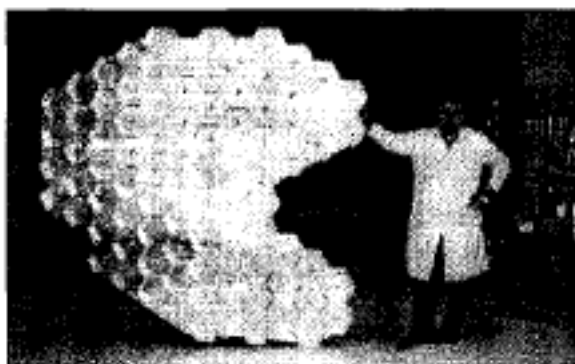


Fig. 6. Phased array feed for Lockheed Martin ACeS antenna (Mecham 1997).

arrays. Few quantitative details are available, and no potential breakthrough area where a sustained R&D program would have immediate impact can be identified.

The problems in phased array design remain what they were in 1992. Electromagnetically, the array must maintain the desired radiation pattern and polarization purity over the transponder bandwidth and the desired scan angle range. Electronically, the array must form and steer beams as fast as onboard traffic routing requires. Mechanically, the array structure must deliver control signals and DC power to (and often rf from) the radiating elements and dissipate heat while not screening the radiating elements. Most experts feel that the ultimate solutions to these problems lie in using photonic techniques to power and control the active elements in phased arrays.

As with large reflector antennas, most satellite manufacturers have competitive phased array technology but keep the details proprietary. Several of the present low earth orbit (LEO) systems (Iridium and Globalstar, for example) leverage technology developed for ACTS and formerly military technology to fly impressive phased arrays. ACeS (Fig. 6) will carry an impressive array feed generating 70 beams at L-band. Proposed Ka-band systems like Teledesic may fly arrays developing hundreds of beams.

The major US primes are working on phased arrays. Typical development models incorporate optical beam forming with true time-delay beam steering, and combine photonic and rf functions on the same chip. A representative example is a 96-element L-band single-beam array achieving 50% bandwidth and a 60 degree scan angle.

Several research satellites with impressive phased arrays are planned. For proprietary reasons, infor-

mation about these is limited. France's STENTOR spacecraft will carry a direct-radiating array made up of 48 subarrays, each fed by its own SSPA. The STENTOR array will develop three independent beams. Japan's GIGABIT satellite array will develop five scanning spot beams, each with a 1.5 degree scan and 559 MHz bandwidth. Its total radiated power will be 500 W.

In 1992, the Europe, Japan, and the United States had ongoing programs in phased array development. Since then, the end of the Cold War has brought former Soviet military technology into the commercial arena. The Moscow Aviation Institute, for example, is developing active phased arrays with multi-element transmit and receive amplifiers and hybrid optoelectronic signal processors.

3.4. Optical beam forming

Optics offers the potential for volume, mass, and power reductions with increased speed relative to similar subsystems implemented using electronics. There continues to be a tremendous amount of research in micro-optics, optical memory, optical signal processing, and optical communications throughout the world.

Diffractive optical components for use in free-space and bulk micro-optical systems are being studied for optical communications, information processing, optical computing and sensor applications. The subject components include high-efficiency blazed micro Fresnel lenses, high-efficiency chirped gratings, Bragg gratings, binary gratings, and arrays and composites of them. Integrated optics technologies are expected to play an important role in the development of new devices for future optical memory systems. There has also been considerable effort in the development of waveguide devices for the communication use, including switches, mode splitters, mode converters and wavelength filters.

Hughes Research Lab, located in Malibu, CA, is jointly owned by Raytheon and Hughes. Research topics includes communications, photonics, and microelectronics. Of particular interest is the work in optical beam forming for phased array antennas. The microelectronics staff is a vertically integrated team of experts in growth and diagnostics of III-V semiconductor materials and related compounds, development of microelectronics processing techniques, design of advanced device structures, modeling, rf/analog/digital circuit design, analysis, and evaluation - all focused on delivering high performance digital, analog, linear,

rf, optoelectronic and mixed-mode circuits for the next generation of microwave, millimeter wave, commercial wireless, and photonic systems.

4. On-board processing¹

4.1. Overview

Processing of communications signals on-board a satellite is a capability initiated in the early 1970s for military satellite communications and first deployed in an operational satellite in the Fleetsat (1978). On-board processing of communications includes capability to do one or more of the following:

- Route signals from an uplink beam to a different downlink antenna beam (at rf or if).
- Phased array antenna beam forming and beam pointing.
- Demodulate signals.
- Decode signals (error correction) including de-interleaving.
- Read headers or addresses and route signals in accordance to rules (precedence and priority).
- Place signals in queues.
- Perform mathematical transforms on received signals or recovered digital files.
- Reformat, remultiplex, re-interleave, re-code, and remodulate; where reformatting may include changing multiple access type for downlink transmission (i.e., uplink CDMA changed to downlink TDMA).
- Rapidly allocate the instantaneous bandwidth to individual transponder channels.

Most of these functions are implementable using digital processing and relate to digital communications. The first and last items (route signals and modify bandwidths) may be implemented using components that are analog in essence, and may be used with analog or digital communications signals. As these concepts do not require 'recovery of bits' from the communications signals for implementation they can be called analog routing and switching. The first item involves electronically controlled rf or IF switches, usually in a matrix format, that can be controlled statically or dynamically, and has been used commercially for some time. The other items in the list may be implemented

by digital processors requiring devices hardened to the radiation environment of space.

Phased array antennas with many fixed or independently steerable beams require a large number of radiating elements with individual phase (and amplitude) control for each beam. This signal control can be implemented with analog circuits (for a small number of beams) or digitally which requires substantial digital processing. Phased array antennas (with fixed beams) are used on the Iridium and Globalstar satellites.

Baseband processing and switching involves functions similar to those performed in terrestrial local area networks and telephone switches. In addition, demodulation, decoding, demultiplexing, switching, congestion control and notification, buffering, remultiplexing, and modulation and network synchronization may be performed. Most of these functions require specialized processors in order to be size/mass/power efficient. This is especially true for packet switched systems with a large number of earth stations - particularly if the system is required to handle multiple user rates.

To date, few commercial onboard processing satellites have been flown; next to TIARSAT, the first experimental satellite with major communications processing, ACTS has logged several productive years of experiments. ACTS has two basic onboard processing packages, a circuit switched baseband package and an IF satellite matrix switch. Both systems are controlled via ground commands, rather than via onboard autonomous control. Compared to some future systems (proposed and under development) these satellites appear rather simple. Iridium is the first large scale commercial satellite system to use onboard processing for end-to-end signal routing through multibeam phased array antennas and intersatellite links. The full system is in commercial operation.

The numerous satellite systems proposed for both Ka-band and V-band (already 17 filings with the FCC) will require advanced onboard architectures for fault tolerance, autonomous control and reconfigurability. In addition, some of these systems propose to use packet switching techniques and intersatellite links as part of the communication payload. Advanced modulation and coding technologies using block coding and concatenated convolutional and block coding will be required to achieve link qualities approaching that of fiber-bit error rates of 10^{10} or better.

There is now a well demonstrated technology base, and experience with real implementations, for most of these capabilities. Only the rapid allocation of bandwidth is at the laboratory stage and has not yet flown on a satellite.

¹ Dr. William Francis of NASA Lewis Research Center contributed to the section on on-board processing.

4.2. Progress in analog routing and switching

The concept of a multiple beam satellite in which the beams cover small areas offers many advantages. This implies routing or switching of uplink signals to different downlink beams. This may be accomplished by receiving all uplink signals and then re-transmitting them to a ground station which rearranges the signals, and retransmits them to the satellite such that the signals are routed to the appropriate downlink beams. Because this introduces two round-trip delays, it is preferable to accomplish the routing in the satellite. This method is referred to as 'IF switching', because it is implemented at an intermediate frequency. The satellite IF switch developed for the NASA ACTS communications satellite is a matrix switch that performs wideband IF switching. This matrix switch can be programmed to perform dynamic switching in a cyclical manner controlled from a master ground station. The technique is termed, satellite switched TDMA (SSTDMA). This form of multiple access and routing will increasingly come into use for higher frequency bands because it preserves wide area routing flexibility while allowing use of very high gain antennas on the satellite.

Studies of the switch for the Advanced Communications Technology Satellite (ACTS) suggest that the design technique is extensible to at least a 100×100 crossbar configuration; however, the switch built for ACTS actually provided only 3 input and 3 output ports.

Another form of processing would be to change the instantaneous bandwidth of satellite transponders. A new device for accomplishing this form of switching is being developed by COMDEV in Canada. The device is being under the trademarked name BEAM*LINKTM and subchannelizes the transponders of a bent pipe payload providing a 30% increase (estimate by COMDEV) in their capacity (i.e., by allowing management or matching of power and bandwidth on an as needed basis). An early form of this processor is currently in use on the INMARSAT 3 constellation of five satellites. Each INMARSAT 3 satellite has two BEAM*LINKTM processors which form the heart of the payload. Each processor contains 168 SAW filters and a total of 70 000 components. COMDEV produces SAW filters as components and as part of subassemblies, primarily as frequency converters for digital payloads.

The BEAM*LINKTM processor divides standard transponder bandwidths into smaller subchannels

which can be independently assigned, combined, and routed to any down link beam. These traffic management processors permit the implementation of Frequency Division Multiple Access (FDMA) based architectures which have enhanced performance, flexibility and functionality over conventional bent pipe payloads.

BEAM*LINKTM provides several other advantages. It permits a point to multi-point broadcast capability without sacrificing significant uplink and/or crosslink bandwidth. Subchannelization enables adjustments of the transponder gain for individual earth terminal classes thereby increasing the power that can be delivered to disadvantaged users and reducing system dynamic range limitations. Finally, BEAM*LINKTM makes it practical to use inter-satellite links on wideband transponding satellites. The Inmarsat and the advanced BEAMLINK processors employ surface acoustic wave technology.

4.3. Progress in digital on-board processing

There are two problems associated with the incorporation of digital processors into communications satellites. The first is the necessity of using hardened devices in the radiation environment of space. The second is the difficulty of heat dissipation which increases with the increase of processor density.

Hardening for the charged particle environment is well understood and degradations can be accurately predicted. While current knowledge does not allow certainty in predicting 'single bit upsets' or 'bit flips' from the next solar maximum, improvement in hardening is certain to lead to longer life, lower launch weight, and reduced vulnerability. These are gradual trends in the technology background.

Radiation hardened processors have been under development for over twenty years. Limited market quantities have inhibited unfunded development, so that components were developed for specific applications. Gradually, the need for processors for use in attitude control and other applications caused first the development of device technology and then packaged computers for space. Hardened components generally lagged corresponding unhardened parts by a year or more, as the unhardened device was used to create prototypes that then identified the need for the hardened counterpart. Device technology emphasized different materials for the space application, such as silicon on sapphire. In the 1990s, manufacture of hardened devices was gradually transformed largely into being a process

problem allowing use of more conventional technologies. Several suppliers became proficient in producing radiation tolerant integrated circuits of high density. In addition, a more general family of hardened component types have become available, including RAM, field programmable gate arrays, digital signal processors (DSPs) and analog to digital converters.

Onboard computers are being developed by a number of companies such as Saab-Ericson and Honeywell (32 bit computer with 16 and 32 bit instruction sets, radiation hardened to 1 Mrad total dose).

Lockheed Martin acquired the division of IBM that developed space hardened logic devices, processors and computers. Lockheed Martin products include the RAD6000 low cost, high performance 32 bit RISC processor that combines the PowerPC single chip CPU with proprietary radiation hardening VHSIC technology. This processor has already been flown on the MARS Pathfinder. Static random access memory chips in CMOS (to 2 Mbytes) are qualified and have flown; SRAM and EEPROM are also available.

Application specific integrated circuits (ASICs) are increasingly being used onboard spacecraft, to reduce mass, size, power consumption and at the same time increase reliability. The drawback of using ASICs is the development cost, risk and schedule, and therefore particular attention is necessary when ASIC design is being performed to improve in speed, power, and densities. For instance, Altera and Xilinx currently have 100 k gate 3.3 V programmable logic devices (PLDs) and expect to introduce 2000 gate field programmable gate array (FPGA) by 1999. UPMC Microelectronics Systems has 16 μ 200 k (400 k by 1998) gate arrays and can provide circuits capable of withstanding 1005 krad total dose and Single Event Upset (SEU) at 10^{10} errors/bit day and 150 MHz clock rates. Devices are available in both 5 V and 3.3 V. UPMC also produces radiation hardened SRAMs, dual port RAMs, and FPGAs. Actel has low SEU devices that are latch-up immune up to 300 krad. These circuits are now being utilized in spacecraft. Iridium uses over 13 different 100 k gate ASICs. As more of these devices are used, confidence should grow.

Intellectual property (IP) and core logic (CL) are third party designs of specific, generic, complex functions that can be licensed and are widely utilized today. These designs may be hardwired for specific ASICs (cell based) or software based using a hardware description language (HDL) such as Verilog or VHDL. Cores are available for a vast array of functions such as network interfaces (ATM, ethernet, etc.), digital fil-

ters, coding, compression, and MPEG-2 to name a few. Utilizing IP/CL allows companies to concentrate on the overall system design without having to design and maintain individual complex functions.

In Canada, Spar concentrates on demultiplexers, demodulators, and uplink access scheduling. A breadboard of a fast packet switch has been constructed but so far there are no plans for ASIC development that would be required for flight. The processor output would interface to a standard ATM switch. Spar is also leading the system engineering work for the Canada Advanced Satellite Program, including analysis of packet switching in a mobile multimedia environment. \diamond

In Europe, Alcatel Telecom plays a leading-edge role in the development of information superhighway technology, including broadband ATM, switching systems and SDH transmission, which are compatible with the Internet. Alcatel has plans to develop Sky-Bridge, a constellation of 64 LEO satellites with onboard ATM capability complementing that of ground infrastructures. In addition to Internet access, the Sky-Bridge system will provide bandwidth-on-demand for other types of high-speed data communications, at speeds up to 60 Mbps. Alcatel has the design and fabrication capabilities to provide OBP technologies including onboard computers, switching and routing, and phased array antenna controls.

Although Alcatel is fully capable of implementing space based onboard processing for commercial applications, the company has developed a 'Switchboard-In-The-Sky' satellite network concept that performs switching in intelligent ground terminals using ATM technologies. This concept is known as 'Cadenza'. With Cadenza, ATM subscriber modules are plugged into a backplane whose plugs and sockets are antenna dishes. The backplane's traditional copper tracks (in ground-based applications) are replaced, in Cadenza, by radio links, and the green fiberglass printed circuit board is replaced by-literally-the sky.

Alcatel Microelectronics, formerly Alcatel Mietec, located in San Francisco, California, markets intellectual property (IP) and 'system-on-chip' (SOC) application specific standard products for wireline and wireless access solutions worldwide. Alcatel Microelectronics will market Alcatel IP and design services to original equipment manufacturers building highly integrated communications products. Alcatel Microelectronics has direct access to the IP developed by over 10 000 telecommunications systems designers at its parent organization, Alcatel. Besides this strong

IP base in communications, Alcatel Microelectronics has also licensed IP from leading vendors worldwide. Alcatel Microelectronics emphasizes advanced methodologies to manage, develop and assemble its IP, using architectural templates that will support 'plug and play' design. These hardware/software co-design techniques allow the company to integrate its IP portfolio in new SOC solutions with continuously shortened design cycles. The company will employ its own advanced mixed signal manufacturing technology for designs requiring the highest level of analog and digital functionality on a single chip.

Alenia (Aerospazio Division) in Italy has wide experience building onboard processing satellite equipment including ASIC Components. Alenia is building Skyplex, a digital TV system that uses technology developed from the ESA OBP work. Skyplex combines six Ku-band digital TV uplinks in the satellite to form a Ku-band DVB/MPEG type downlink. This equipment was scheduled to fly on EUTELSAT's Hotbird 4 in early 1998. This onboard processor has 33 MHz bandwidth, 6.8 kg mass, $24 \times 25 \times 18$ cm dimensions, and uses 43 W of prime power. It contains down- and up-converters, demodulates 6 digital carriers (2 Mb/s); and combines the data streams for retransmission. An improved model with up to 18 channels is under development.

ESA requires ASIC manufacturers to utilize the VHDL hardware description language (VHDL) for use in all phases of the creation of electronic systems to minimize development risks and avoid finding 'unpleasant surprises' are late in the development cycle, from ensuring that the correct specification is established, to using a design methodology and IC technology suitable for high-reliability designs. This design methodology also enables reuse of ASICs for similar applications, if sufficient care has been taken during the development. ASIC technologies commonly used for space applications include: ABB Hafo (S) $1.2 \mu\text{m}$ and $2.0 \mu\text{m}$ CMOS/SOS (silicon on sapphire); GPS (UK) $1.5 \mu\text{m}$ CMOS/SOS; TEMIC/MHS $0.8 \mu\text{m}$ and $0.6 \mu\text{m}$ CMOS; TCS $1.0 \mu\text{m}$ and $0.8 \mu\text{m}$ CMOS SOI (silicon on insulator).

In Sweden Saab Ericson Space develops and manufactures a large variety of spacecraft equipment including onboard computers and data handling systems including the computers for the first four SPOT earth observation satellites. The development of new computers for the SPOT-5 and the forthcoming large European satellite for environmental monitoring, Envisat, is in progress. Saab Ericson Space has developed its

own fault tolerant microprocessor, THOR, specially designed to suit space computer applications requiring high reliability, long life and low sensitivity to cosmic radiation. THOR is also adapted to the ADA programming language, has been successfully tested in space, and will be used in the next Swedish satellite project, ODIN, to control satellite positioning in orbit. The company also led the industrial team that developed the space version of the SPARC microprocessor, ERC32. Products based on ERC32 are now available.

In Italy Telespazio is involved in specific programs and projects for telecommunications that include onboard processing. ITALSAT is a multibeam (six beams using two antennas) digital system that operates in the 30/20 GHz (uplink/downlink) frequency bands, providing onboard switching of signals using a baseband matrix switch. ITALSAT F1 was launched in January 1991. ITALSAT F2, launched in 1996, provides multibeam capabilities at 30/20 GHz as well as ISDN capability. Program objectives are:

- investigate innovative onboard signal regeneration and switching technologies;
- evaluate performance of a digital satellite network integrated into the terrestrial network;
- collect additional data with which to better understand the propagation impairments that must be overcome in using 30/20 GHz (and higher) frequency bands for satellite telecommunication.

In onboard switching technology, Telespazio is the prime contractor to ESA on Phase B activities for an advanced satellite system known as OBP. The Phase B activities encompass two main efforts: (1) to define the system and develop system specifications, and (2) to develop a laboratory model of the OBP that will include an engineering model of the onboard baseband switch matrix. The major technical innovations of the OBP package are as follows:

- new generation VSAT networks that will provide higher data rates and full interconnectivity on demand;
- ISDN services;
- multiple-stage baseband matrix, employing time-switching stages (T-stages);
- multiple-frequency TDMA for uplink access with a 'very tight' synchronization scheme (to realize symbol synchronous operation) to achieve very efficient exploitation of the uplink capacity;
- experimental and pre-operational phases currently planned will use a 'reduced OBP payload' on the proposed ITALSAT F3, which could be launched as early as 2000.

In Japan CRL is planning ETS-VIII. This satellite is in the design stage and is expected to be a three ton GEO satellite that will be used primarily for studies of multimedia mobile communications between a base station and small, mobile terminals. Some onboard processing is anticipated including an onboard switch and computer system utilizing radiation hardened gate arrays with an SRAM based memory. This system will be ground controlled and include a 1 Mbps packet switch system. Non-packetized voice and packetized data will be handled by separate switches.

CRL is also proposing a K/Ka-band 'Gigabit Satellite' which will address gigabit (1.2-1.5 Gbps), very high data rate (155 Mbps) and broadband multimedia (1.5-155 Mbps) users. The gigabit links will use SS/TDMA while the others use SCPC/TDM uplinks and TDM/TDMA downlinks with onboard ATM switching.

In the United States, the Aerospace Corporation studied the financial and technical tradeoffs involved in OBP systems. They performed a study for the European Space Agency on the communications payload for the ICO system to determine if an all digital processing repeater for about 5000 voice circuits was feasible. The study identified several alternative architectures and how they scaled with the number of circuits. The conclusion was that the approach of using an FF polyphase filter bank with narrowband channelization implementable with available chips resulted in the minimum power and was attractive.

Several satellite programs ongoing at Hughes Space Communications (HSC) include onboard processing; among these are the 12 satellites for ICO Global Communications (London) that use phased array antennas with digital beam forming in addition to baseband communications processing. HSC anticipates the density and the layout of radiation hardened chips to reach the levels of today's standard CMOS in a few years. In addition, work in the industry is expected to extend CMOS chips to 8 million gates; extend InP devices to operate at 200 GHz; and enable the production of new SiGe HBT devices. OBP technology development for phase array antennas and their associated processors are considered very important for future communications satellites.

L-3 Communications Systems-West is actively engaged in unique technology development for specialized airborne antennas, wideband spread spectrum, multiplexers, modems, and command/control hardware. Of special note is L-3 development of image compression and ASICs for modulator functions. The

modem ASICs are highly programmable to accommodate multiple data rates and modulation types. L-3 is completing development of an ASIC that will accommodate BPSK, QPSK and 8 PSK modulation with or without direct sequence spreading and data rates up to 140 Mbps.

Motorola has launched the Iridium satellite system, the first operational commercial use of onboard processing with onboard demodulators, switching, and routing as well as orbital location control. The onboard processor has been constructed using 178 very large scale integrated circuits (VLSIs) designed specifically for the project. It includes 512 demodulators, with closed loops (via control channels to the handheld units). For the Iridium satellite, each user shares 45 ms transmit and 45 ms receive frames in channels that have a bandwidth up to 31.5 kHz spaced 41.67 kHz apart. All users are synchronized so that they all transmit and all receive in the same time windows, alternatively. Motorola has extensive plans to develop further commercial satellite systems that require extensive OBP technologies with an order of magnitude greater capability than the Iridium system.

Motorola also developed the onboard circuit switch for the ACTS satellite which utilizes TDMA uplinks at 27.5 Mbps and TDM downlinks at 220 Mbps. The switch is controlled from the ground.

5. Progress in TWTs and EPCs

5.1. Introduction

A principal elements of any spacecraft payload is the transmitter, consisting of a power amplifier and its associated power supply. This amplifier is usually operated close to saturation (maximum output power level) in order to attain high efficiency of converting dc energy from the solar arrays into useful radio frequency (rf) energy that carries the communications. An efficient transmitter produces by nature signal distortions and other impairments that decrease the communications capacity. The best compromise between output power and distortion is a function of the communications signals being amplified.

Two types of transmitters are used in commercial satellites, traveling wave tube amplifiers (TWTAs) and solid state power amplifiers (SSPAs). In TWTAs, the power supply, often called the electronic power conditioner (EPC), supplies a number of high voltages (usually several kilovolts), which presents some design challenges.

Table 3
NEC TWT product line

Frequency (GHz)	2.5	4	12	20	22	26	30	44
rf-Power (W)	120	5	20-170*	2-30	80-230	20	20	20

* >250 W under development.

5.2. Traveling wave tube amplifiers and EPCs

There remain only three manufacturers of space qualified TWTs in the world, Thomson (including AERG, Ulm, Germany) in Europe, Hughes EDD in the United States and NEC in Japan. In Japan Toshiba has built TWTs for space use, however, this manufacturer does not currently have a substantial market share.

5.2.1. Market

Currently the worldwide TWT market (including commercial and military ground and space applications) is on the order of \$500 million; the US market alone is about \$250 million. The worldwide market in commercial space TWTs was estimated at approximately \$140 million in 1996. Including military applications, the total space TWT market might amount to as much as \$250 million. Customers for space TWTs are the satellite manufacturers, and in particular payload manufacturers. These are not just located in the United States but are now distributed worldwide and include Russia. Worldwide production of space TWTs is currently about 1200 tubes per year, the majority split between Hughes and Thomson. Most of these TWTs have a lifetime in excess of 15 years. Both these manufacturers have a complete product line from L-band to above 30 GHz with just about any rf power level desired.

All TWT manufacturers have the capability to build EPCs and integrate them into TWTAs. At Hughes the emphasis is on TWTs, EPCs, and integration of those components into TWTAs. There are several ways in which the TWT and the EPC can be integrated to form a TWTA. Today many times the TWTAs are integrated by the TWT manufacturer (Hughes EDD and NEC); frequently the satellite payload manufacturer procures the TWTs and integrates them with its own EPC (Hughes, Lockheed-Martin) or uses a third party EPCs. In Europe the major manufacturer of EPCs is Bosch Telecom GmbH, formerly ANT. Each integrates its own EPC with, typically, Thomson (or AERG) TWTs to provide the complete transmitter package to a spacecraft builder. As with the space TWTs, high efficiency is a prime objective for the EPCs. Today's best EPCs

achieve efficiencies of over 90%. (Hughes has demonstrated efficiencies as high as 94%.) Further development work (a switching speed increase to 150 kHz) is expected to lower the EPC mass of a Ku-band EPC (currently approximately 1300 g) to less than 900 g.

In Japan both NEC and Toshiba have developed TWTAs for space use. For a 22 GHz broadcast application Toshiba developed a 230 W coupled cavity radiation cooled TWT and NEC developed a helix TWT (1.1 kg) with variable power from 80 to 230 W (adjustable by ground command) and 54.4% peak efficiency. This TWT does not require a radiator for cooling thanks to diamond rod helix supports. The EPC for both tubes runs around 12 kV and both have flown on the COMETS satellite. NEC has developed a product line of tubes from S-band to 44 GHz, as listed in Table 3.

On the basis of information gained from site visits the WTEC study team concludes that there is a balanced competition between the European and US TWT manufacturers. Actual hardware delivered into space shows the Japanese TWT industry to be trailing both Europe and the United States.

5.2.2. R&D activities

AERG provided an informative graph (Fig. 7) showing the improvement of TWT efficiency over time and projections up to the year 2004.

Improvement in TWT efficiency over the last few years is due in large part to very sophisticated software modeling and optimization using proprietary computer programs. The availability of new techniques and software to perform 3D electromagnetics calculations has allowed designers to model TWTs much more accurately and has helped substantially in the design and optimization effort. Further developments of TWT technology will continue to improve the performance. Over the next few years TWT efficiency is expected to improve gradually; no major breakthroughs in technology are expected. For instance, diamond helix supports are expected to bring a small improvement in efficiency. Adding another collector is likely to increase the efficiency by another 2% while the EPC changes to accommodate a 5th collector are minimal. For all manufacturers, increased efficiency, reduced

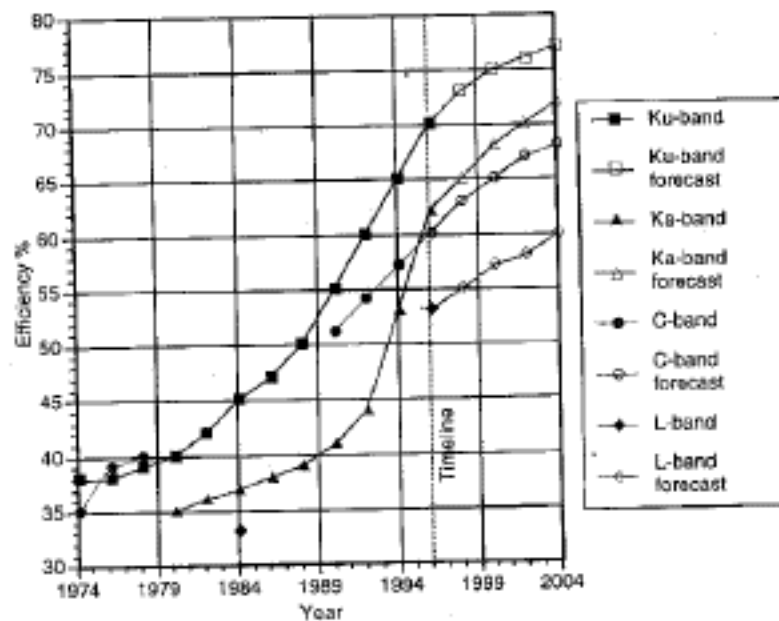


Fig. 7. TWT efficiency vs. time (Thompson).

Table 4
Current status of HAC EDD TWT performance

Frequency band	Current production	Demonstrated
S-band		
rf output (W)	120	150
Efficiency (%)	62	64
Mass (g)*	1200	1200
C-band		
rf output (W)	120	140
Efficiency (%)	59	62
Mass (g)*	800	800
Model#	8556	8556#50
Ku-band		
rf output (W)	135	170
Efficiency (%)	65	70
Mass (g)*	850	700
Model#	8898	8815
Ka-band		
rf output (W)	70	140
Efficiency (%)	55	60
Mass (g)*	850	TBD
Model#	966H	9130H

Ka-band TWTs have 3 GHz bandwidth.
*add 350 g for radiation cooled option.

mass, and improvements in producibility are important goals.

Table 5
Current status of Thomson/AERG TWT performance

Frequency band	Current Laboratory	Forecast in 2000
L-band		
rf output (W)		
Efficiency (%)	52	60
C-band		
rf output (W)	60	120
Efficiency (%)	60	67
Ka-band		
rf output (W)	140	220
Efficiency (%)	72	78
Ku-band		
rf output (W)	120	140
Efficiency (%)	63	72

The efficiency of an S-band TWT would fall between L-band and C-band.

In the future the top TWT efficiency will climb over 70%, operating frequencies and power levels will increase and the mass of both TWTs and EPCs will further decrease. Table 4 provides the current status of space TWTs at HEDD.

The current status and forecast for Thomson/AERG space TWTs is listed in Table 5.

The current performance of NEC space TWTs is listed in Table 6.

Table 6
Current status of NEC TWT performance

Frequency band	Current performance
S-band	
rf output (W)	120
Efficiency (%)	52
Ku-band	
rf output (W)	170
Efficiency (%)	66
Ka-band (21 GHz)	
rf output (W)	230
Efficiency (%)	55
V-band (44 GHz)	
rf output (W)	35
Efficiency (%)	41

6. Optical communications and intersatellite links

6.1. Introduction

Space-based, free-space optical communications is a concept that has been around for many years. In the last few years, however, there has been impressive activity to bring the concept to fruition in civilian and government non-classified projects. Today's market for space-based optical communications is primarily intersatellite links (ISLs) which are the main focus of this chapter. There is also a place for high data rate (many Gbps) space-earth links, though propagation effects due to the atmosphere and weather make this a much more difficult link. Some activity in space-earth optical communications will also be covered here.

The usual parameters that system designers want to optimize drive the desire to utilize optical communications onboard a satellite: size, weight and power – and of course, cost. Under ideal assumptions about equivalent efficiency of signal power generation, detectors, and receiving surfaces, link equations show that optical communications systems with telescope aperture equivalent to that of the antenna of a radio frequency (rf) system could potentially provide tens of dBs of link efficiency improvement, e.g., data rate, margin, etc. This is results strictly from the wavelength difference. These tens of dBs can be traded off against reduced optical aperture size, hence reduced size and weight, and the inefficiencies of optical signal generation/detection, and yet still support increased data rates relative to an rf system.

One significant factor in this trade-off is that the optical system will typically have a much narrower

beamwidth than the rf system. This has both a positive and negative side. On the positive side, a narrower beamwidth means that the potential for interference to or from adjacent satellites will be reduced. This is particularly important in large LEO constellations. On the negative side, the requirements for more accurate pointing, acquisition and tracking (PAT) and the impact that this may have on the spacecraft could impose an unwelcome burden. Accurate PAT is critical to the acceptance of optical ISLs.

A secondary, though not unimportant, fact about optical communications is that, unlike the rf spectrum which is regulated by national and international agencies, the optical spectrum is currently unregulated.

Finally, reliability of optical communications systems, particularly their lasers, has been a concern in the past. This issue is being overcome by advances in optical and laser technology but needs documented space validation for wider acceptance.

6.2. Applications

Intersatellite communications is used primarily for 'networking' a constellation of satellites at data rates up to many Gbps or for data relay purposes from tens of Mbps up to Gbps. These ISLs can be between all the various orbits that one might consider: low earth orbit (LEO), medium earth orbit (MEO), highly elliptical orbit (HEO), and geosynchronous earth orbit (GEO). There are currently systems like Iridium and NASA's Tracking and Data Relay Satellite System (TDRSS) that are using rf ISLs for these purposes. The ill-fated Japanese COMETS was to use rf ISLs. There are planned systems like ESA's ARTEMIS that will use rf and optical ISLs in the future. It is safe to say, however, that for many of the reasons outlined above, the future belongs to the optical ISL. This is evidenced by the fact that most, if not all, of the commercial satellite constellations now being announced, such as Teledesic, will be using optical ISLs. Iridium considered an optical ISL, but did not fly it primarily for business reasons, i.e., the risk perceived by investors.

Space-Earth links have been, and continue to be, primarily rf. Because of the advantages of optical systems related in the introduction earlier, Japanese, European and US researchers are investigating optical space-earth links from LEO as well as the far reaches of outer space. Optical links face a severe disadvantage due to the effects of the atmosphere and weather. Solutions include adaptive optics, spatial diversity, and onboard storage with burst transmission under good con-

ditions. The first applications are likely to be in scientific satellites but as operational methodologies are developed, space-earth optical links will work their way into commercial systems.

As will be shown below, space-based optical communications development around the world has been primarily supported by government agencies. The European Space Agency, the Japanese government, and NASA and the DOD in the United States have been the main funding agencies. This is changing as the commercial satellite world integrates optical ISLs, and companies will be willing to form partnerships and invest more of their own independent research and development funds.

6.2.1. Japan

The Japanese have a strong program in optical communications [7]. The Science and Technology Agency has designated the Communications Research Labora-

tory (CRL) of the Ministry of Posts and Telecommunications as a Center of Excellence for Optical Communications and Sensing. Thus the government has determined that optical communications and optical technologies, including sensing, are extremely important issues for Japan. As a Center of Excellence, the CRL has gathered researchers from around the world and devoted a lot of money for developments in this area. An overview of the types of links and systems being considered, from ISLs to space-earth links, is shown in Fig. 8. A comment was made during the site visit to CRL that all ISLs of the future would be optical.

It is a fairly broad-ranging program with increasing goals as shown in Fig. 9 from CRL. Current plans call for investigation of multichannel medium bit rate (300 Mbps) systems using $0.8 \mu\text{m}$ wavelength technology while simultaneously developing high rate (1.2 Gbps) systems using $1.5 \mu\text{m}$ technology, which is

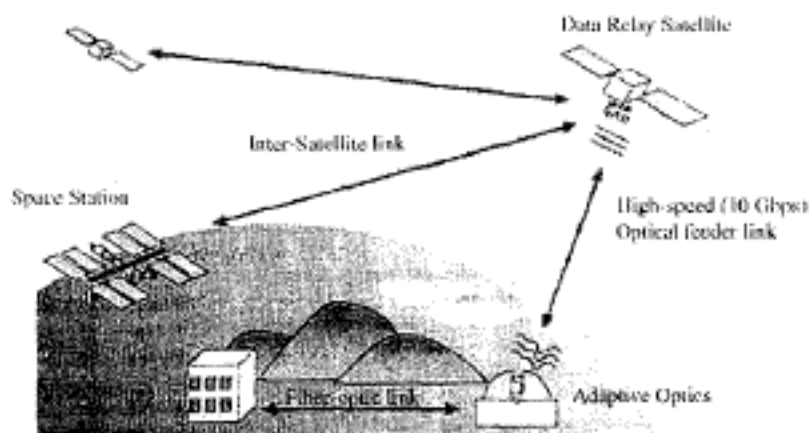


Fig. 8. Japanese optical communications system plan (CRL).

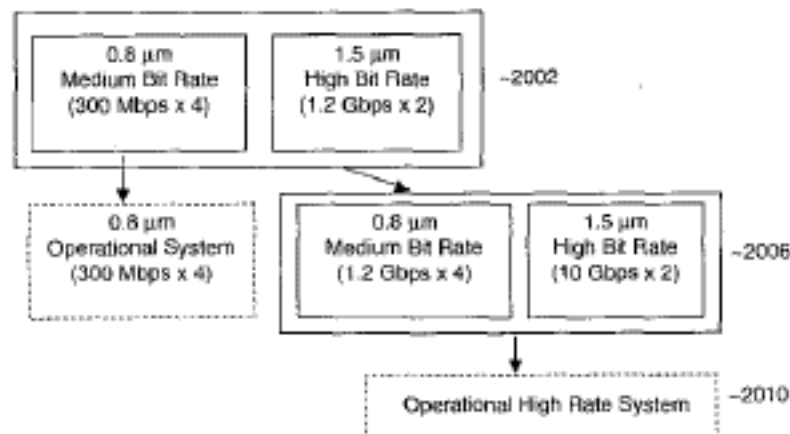


Fig. 9. Performance targets.



Fig. 10. ETS-VI LUCE.

more commonly available, due to terrestrial fiber systems development. In a ten year time frame, the plan is for operational 10 Gbps/channel operational systems.

The main players in the Japanese space-based optical communications world are NASDA and CRL from the government side and NEC on the industry side. NEC has been the main contractor on most of the payloads so far, although a number of companies – Toshiba and others – are involved in making the parts for these payloads.

The Engineering Test Satellite VI (ETS-VI) was intended to go into GEO. It did not achieve this, however, and lasted from 1994 to 1996, its lifespan a result of the effects of being in the wrong orbit. CRL and NASA's Jet Propulsion Laboratory (JPL) were able to do some space-earth experiments during the life of the spacecraft. It provided a bi-directional link at 1.024 Mbps using intensity modulation and direct detection (IM/DD). The spacecraft used a 7.5 cm diameter telescope. The downlink used a 0.83 μm , 13.8 mW AlGaAs laser diode. The uplink was at 0.51 μm using an argon laser from a 1.5 m telescope in Tokyo. The Laser Communications Experiment (LCE) is shown in Fig. 10. Its mass was 22.4 kg and it consumed 90 W max.

The Optical Inter-Orbit Communications Engineering Test Satellite (OICETS) will be launched into LEO in the year 2000 carrying an optical terminal. It will be compatible with the European SILEX terminal and will communicate with the ESA ARTEMIS satellite in GEO. The Laser Utilizing Communications Exper-

iment (LUCE) will have a 26 cm telescope with a 50 Mbps intensity modulated 0.847 μm , 200 mW laser diode link to ARTEMIS and a 2.048 Mbps direct detection link at 0.819 μm from ARTEMIS.

The Japanese Engineering Module (JEM) on the International Space Station will have an optical communications package. It will consist of a 1.5 cm aperture telescope and use 1.5 μm technology to provide 2.4 Gbps links from JEM to earth and to other satellites.

6.2.2. Europe

In Europe, ESA has been a primary driver in the development of optical communications although there have been a number of national efforts also. ESA is developing the ARTEMIS satellite (Fig. 11) which is going to launch on a Japanese H-2 rocket in the year 2000. It will be used for data relay type applications from LEO satellites to GEO. One of the ISL capabilities will be optical. It will also have the capability of communicating to an earth terminal in the Canary Islands using the same ISL terminal.

The main players in Europe are ESA and the national governments, particularly the UK, France, and Germany on the government side and Matra Marconi Space (UK and France) and Oerlikon-Contraves on the industry side. The ARTEMIS satellite will have an optical package onboard (Fig. 11).

Semiconductor Intersatellite Link Experiment (SILEX).

Both LEO and GEO SILEX terminals (Fig. 12) built by Matra Marconi Space in France are complete and ready for integration into ARTEMIS and the SPOT-4 earth observing satellite. SPOT-4 was successfully launched in 1998. The SILEX terminal has a 25 cm aperture telescope with characteristics similar to those reported above for the OICETS terminal. The SILEX terminal has been tested and is performing in accordance with specifications. The maximum range is 45 000 km.

Figure 13 shows a notional view of a number of optical ISL terminals that have been under development under either ESA or national funding in Europe. There is a plan in this vigorous development of optical technologies. ESA has looked at various applications – LEO to GEO, GEO to GEO – and has been developing a wide set of terminals to satisfy these needs and in a lot of different places.

Small Optical User Terminal (SOUT). Matra Marconi Space (UK) developed SOUT which is compatible with SILEX, though in a much smaller package, for LEO-GEO applications (Fig. 14). This is what they call the elegant breadboard (prototype) that was com-

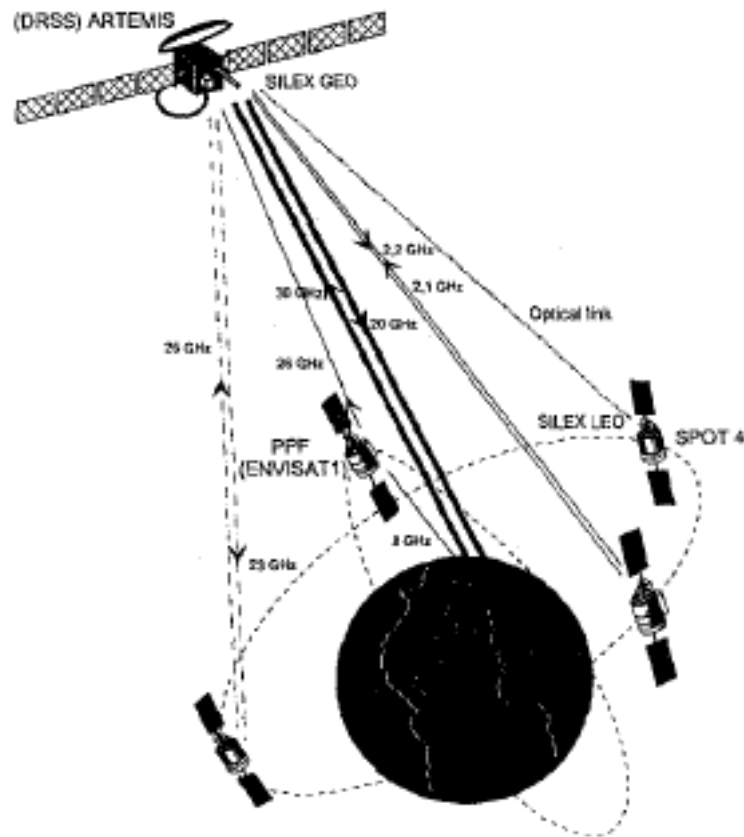


Fig. 11. ARTEMIS.

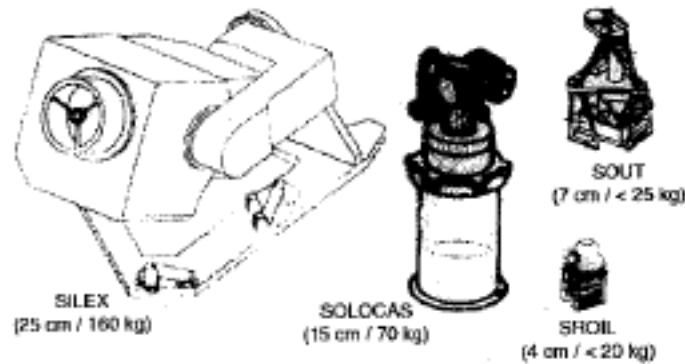
- GEO and LEO flight models complete and ready for integration
 - Matra Marconi Space (Fr.) prime
 - 1998 SPOT-4 launch
 - 2000 ARTEMIS launch
- Characteristics
 - 25 cm aperture telescope
 - LEO->GEO
 - 50 Mbps Intensity Modulated 0.847 μm with 120 mW laser diode
 - GEO->LEO (not implemented on SPOT-4)
 - 2.048 Mbps Direct Detection 0.819 μm for communications and 0.801 μm for tracking beacon
 - Max range 45,000 km



Fig. 12. SILEX.

pleted in 1995 but is not space-qualified. It has a 7 cm aperture and is capable of 2–10 Mbps using IM/DD and a 0.8 μm AlGaAs laser diode. The package mass is 25 kg and it consumed 40 W.

Small Optical Telecommunications Terminal (SOTT). SOTT is a GEO-GEO terminal capable of 1 Gbps. The terminal definition was completed in 1996 by Matra Marconi Space (UK) for ESA. It was based upon a



- Very active and diverse development programs though SILEX is only space qualified system
- Matra Marconi Space (UK and Fr), and Oerlikon-Contraves

Fig. 13. European optical terminals (from ESTEC).



Fig. 14. Small optical user terminal (Matra Marconi).

20 cm aperture $0.85 \mu\text{m}$ 2 W laser and used IM/DD. The package had a mass of 45 kg and required 100 W of power.

Solid State Laser Communications in Space (SOLACOS). SOLACOS was a German national government funded project at Dornier Satellitensysteme GmbH. It is somewhat different from the other terminals presented in that it uses a solid state laser and uses coherent reception. It was developed for GEO-GEO applications with a bit rate of 650 Mbps. It has a 15 cm aperture and uses a $1.604 \mu\text{m}$ 1 W pumped Nd:YAG laser. Coherent reception uses the 'SyncBit' method. It is a relatively large unit at 70 kg. The terminal breadboard was completed in 1997.

Short Range Optical Intersatellite Link (SROIL). The latest ESA development is the SROIL (Fig. 15) under development at Oerlikon-Contraves. The initial version is designed for LEO constellation-type applica-

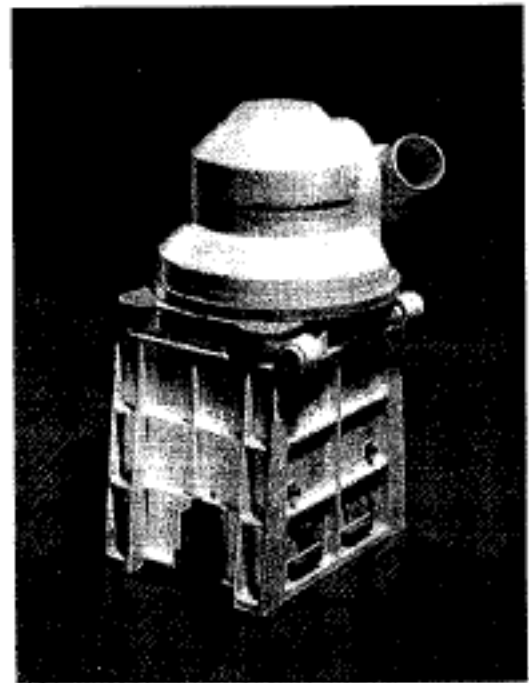


Fig. 15. Short range optical intersatellite link (Contraves).

tions with ranges up to 6000 km. It has a 4 cm aperture, is capable of up to 1.2 Gbps, uses BPSK with homodyne detection ('SyncBit'). This version has a mass of 15 kg and uses 40 W of power. Contraves advertises other versions of the SROIL that can be used even up to GEO-type ranges.

6.2.3. United States

The United States has a long history in space-based optical communications development as evidenced by

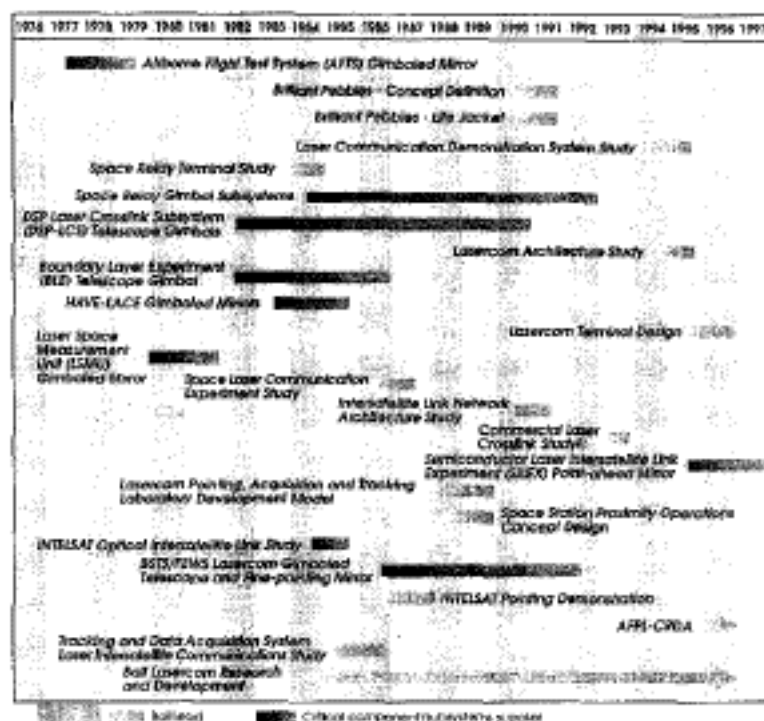


Fig. 16. Ball Aerospace activities since the 1970s.

the Ball Aerospace chart (Fig. 16) from Ball's web site. Until recently, the US effort has been primarily directed towards military/government endeavors. Unlike the European and Japanese programs, much of the information about these systems has been classified or at least dated if available. Recently, with the realization that optical ISLs are an excellent business line, the US companies involved have begun marketing their products more openly and aggressively, and in fact reworking them to fit the more aggressive cost targets of the commercial world.

Even within the military, sponsors like BMDO and SSDC have lately funded optical terminal development that has been available in the open literature to some extent. ThermoTrex developed an airborne terminal for SSDC. Astroterra is currently building a system for BMDO that is going to fly on the STRV-2 spacecraft that will launch in 1998 and is currently going through integration and testing (Fig. 17). The terminal characteristics are shown in the figure.

Recently (fall '97), Ball Aerospace and COMDEV of Canada have announced a new joint venture, Laser Communications International, to compete in the optical ISL market. This merger capitalizes on Ball's long history in optical communications and COMDEV's commercial space experience with the Iridium rf ISLs.

The joint venture has chosen a $1.55 \mu\text{m}$ terminal based upon the investment already being made in terrestrial fiber-based systems at this wavelength and after a study by Ball, SDL, Lucent and USAF Phillips Laboratory showed that this fiber-based technology was space qualifiable. A prototype $1.55 \mu\text{m}$ terminal is shown in Fig. 18. On-Off Keying modulation is the selected method though DPSK is also still considered as a possibility.

Raytheon, a company with a long history in optical sensing systems, has also recently begun development of optical communications terminals for the ISL market. Its terminal is based upon a proprietary liquid crystal optical phased array (Fig. 19) for beam steering. For most of the same reasons as above, Raytheon has chosen $1.55 \mu\text{m}$ for its terminal with a data rate greater than 1 Gbps. It has also chosen intensity modulation with direct detection because of its simplicity.

The MIT Lincoln Laboratory and NASA's JPL have programs for US military and NASA optical communications needs respectively. Lincoln has long been developing 1 Gbps (and faster) communications terminals. Figure 20 is an example of a 1 Gbps DPSK testbed that has been a benchmark by which other developments have been measured. It is based upon a $1.55 \mu\text{m}$ wavelength and erbium-doped fiber ampli-

- Terminal being built by AstroTerra for Ballistic Missile Defense Organization
- Will fly on STRV-2 spacecraft in 1998
- Currently undergoing alignment/testing prior to integration

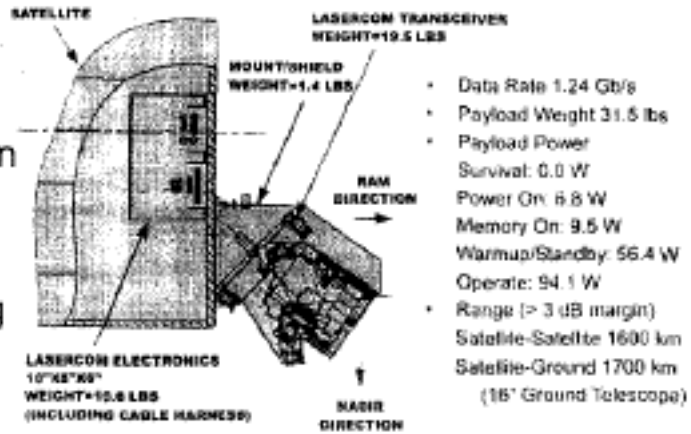
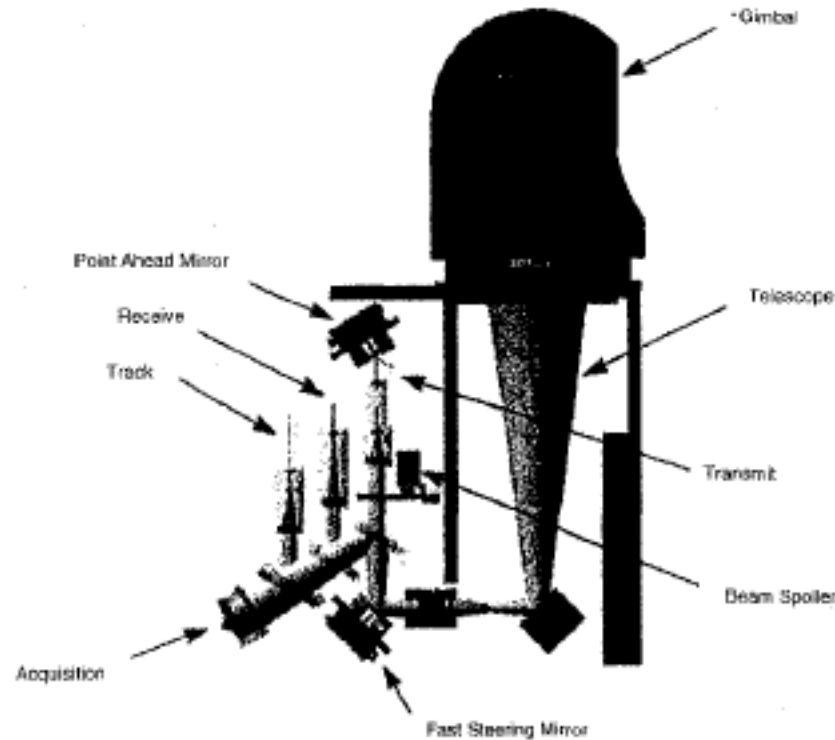


Fig. 17. Astrolink-1000 terminal.



1,550 Prototype Hardware

Fig. 18. Prototype ISL terminal from Laser Communications International.

fier technology. Lincoln also has developed a convolutional encoder and a decoder operating at these high bit rates for the free-space optical channel. Lincoln Laboratory will be responsible for the laser communications package to be carried on the National Reconnaissance Office's Geosynchronous Lightweight Tech-

nology Experiment (GeoLite) satellite. This package will be used to test space-earth optical communications links - particularly to assess atmospheric effects. TRW will be responsible for the satellite integration. Few technical details are publicly available concerning the capabilities of this package. At JPL, the empha-

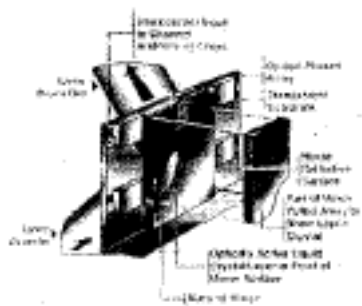


Fig. 19. Raytheon optical phased array.

1 GBPS OPTICALLY-PREAMPLIFIED DPSK SYSTEM TEST BED

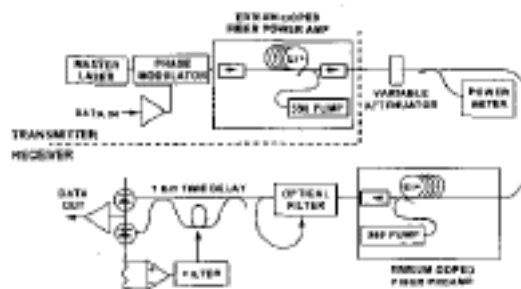


Fig. 20. Lincoln Laboratory 1 Gbps testbed system.



Fig. 21. NASA/JPL Optical Communications Demonstrator.

sis has been on space-earth communications at planetary distances which usually support only hundreds of kbps or a few Mbps, but the 10 cm aperture Optical Communications Demonstrator (OCD) shown in Fig. 21 is capable of up to 250 Mbps and is being upgraded to 1 Gbps capability for near-earth experiments. It is based upon $0.86 \mu\text{m}$ technology and uses on-off keying at the higher bit rates. A version of the OCD being developed for outer planet missions will use pulse position modulation.

In addition to those mentioned above, other potential suppliers of optical systems in the United States are Hughes, Boeing, TRW, and Lockheed Martin.

6.2.4. Trends

In general, smaller, better, and faster characterize the next generation systems. The single most identifiable trend is towards speed. This has been a dominating factor in keeping pace with terrestrial fiber systems. Ten Gbps systems will appear within the next few years. Higher power lasers and higher speed laser switching are aiding in achieving this, along with high speed electronics (ASIC and MMIC). There does not appear to be universal agreement concerning wavelength. A lot of the earlier work was done at $0.8 \mu\text{m}$ but there are now terminals at $1.06 \mu\text{m}$. High-volume development associated with terrestrial fiber systems make components like Erbium-doped fiber amplifiers attractive for space-based optical communications, so many of the recent systems are focusing on the $1.55 \mu\text{m}$ range. Regarding smaller terminals, there is a coalescence of elements in the terminal, making use of the same detectors and a lot of the same electronics for doing multiple functions. Similarly, lighter components will be developed with new materials that will make these systems lighter in general.

In conclusion, Japan and Europe have had very vigorous and open development in optical communications terminals and systems. The US providers have been somewhat hampered by previously classified programs but this is rapidly changing and many US companies are competing with the European and Japanese companies for the growing ISL market. It should be clear to everyone that optical ISLs are coming. When? It should be soon since it is an important application. The first time a Teledesic or some other company deploys an optical ISL in a commercial system may well open the floodgate. Once these systems are in orbit and functioning many others will follow. Space to earth is a little trickier because of the atmospheric effects, and the fact that adaptive optics need to be developed, but there will be commercial applications of high data rate space-earth optical links in the near future.

7. Other enabling technologies

7.1. Progress in electric propulsion

There are three broad categories of electric propulsion for communications satellites, according to the mechanism transferring electric power to kinetic energy: electrothermal, electromagnetic and electrostatic. Electrothermal propulsion includes resistojets and arcjets (performance of the chemical propellant is augmented by electrical heating) and is used on operational satellites. rf or microwave heated thrusters are in the research stage. Electromagnetic propulsion includes pulsed plasma thrusters (PPT) using Teflon as propellant (low thrust, LEO orbit and attitude trimming). Electrostatic propulsion includes stationary plasma thrusters (SPT) and ion thrusters (rf and electron bombardment). Some characteristics and development status are listed in Table 7.

Despite a long history of development (NASA flew an ion thruster on ATS-6) and extensive use of stationary plasma thrusters (using the Hall effect) on satellites in the former Soviet union, electric propulsion had not yet found widespread adoption in commercial communications satellites at the time of the previous study (1992/1993).

In contrast, the last few years have seen a substantial change in the perception of electrical propulsion as several manufacturers have adopted some form of electrical propulsion system for north-south station keeping (NSSK) in GEO satellites and are considering it seriously for LEO application to raise the orbit after launch. Resistojets are used on the Iridium satellites, Arcjets have been used (Lockheed Martin satellites) and the first operational ion propulsion subsystem is flying on a commercial satellite (Hughes HS 601 HP satellite). In addition, there is work in electric propulsion which is not specifically aimed at commercial communications satellites: a 26 kW arcjet and Hall thrusters (4.5 kW and 10 kW).

In today's GEO satellites, with bipropellant systems for apogee insertion and station keeping, the fuel

amounts to about half the total mass in GTO. Electric propulsion can reduce the propellant mass needed for station keeping substantially in exchange for significant use of electrical power (the spacecraft battery may have to be used for several hours per day).

Another attractive application of electric propulsion is orbit raising for LEO and possibly GEO satellites. As the time from LEO to GEO may be substantial (several months) an operator may not want to wait that long without collecting revenue. On the other hand, electric propulsion is an attractive alternative for raising a LEO orbit as only a few weeks are necessary and the satellite can be used during this time. Finally, electric propulsion may be used for the final deorbiting of an obsolete satellite. Table 8 gives a summary of where electric propulsion may be used advantageously for communications satellites.

Hughes has continued development of ion thrusters using xenon as propellant (the program started under NASA and INTELSAT sponsorship) and is life testing two models called XIPS (two models developed, 13 cm diameter and 25 cm diameter with approximately 110 mN thrust, a specific impulse of 2675 s and 2.35 kW power consumption). Hughes is using ion thrusters on commercial satellites launched in the past year. The units are used for station keeping and also during transfer orbit transfer.

In the last few years electric propulsion technology developed in Russia has become attractive to Western commercial companies. Although many devices using this technology have extensive flight history in the former Soviet Union, additional work is necessary to make the hardware suitable for use on commercial satellites. Multinational efforts are under way to make use of the technology and produce hardware qualified to Western standards. One example is a joint venture, International Space Technology, Inc. (ISTI) (founded by SSL, Fakel and RIAME and including SEP and Atlantic Research) that has integrated Russian and US components into an electric propulsion subsystem and performed a complete qualification program. The subsystem consists of a Russian 100 mm

Table 7
Categories of electric propulsion

Category	Engine	Thrust mN	Specific impulse m/s (metric units)	Specific impulse s (US units)	Development Status
Electrothermal	Arcjet	100–200	5000–6000	500–600	Operational
Electromagnetic	PPT (Teflon)		<11	~9800	~1000 Experimental
Electrostatic	SPT	50–200	16 000–18 000	1600–1800	Operational/Qualified
Electrostatic	Ion engine	10–120	25 000–30 000	2550–3000	Operational/Res.

Table 8
Applications for electric propulsion

Orbit needed	Delta v needed m/s	Satellite Mass kg	Thrust mN	Time	Power kW
GEO station keeping	50/year	2000-4000	20-200	2-6 h/day	1.2- 2.5
HEO orbit control	100/year	2000-3000	10-250	3-6 h/day	2-2.5
GTO	5 k-15 k	5000-8000	100-2000	3-12 months	3-5
LEO/LBO orbit raising		20	300-1500	10-100 weeks	0.5-1

stationary plasma thruster (SPT-100) and xenon flow controller, a US power processing unit, tank and propellant management assembly [8]. At least two satellite manufacturers have expressed interest in using such a subsystem. Currently, a disadvantage of this type of thruster is the wide divergence of the exhausted jet. Research in Russia (sponsored by SEP) is addressing this problem.

The two European ion thrusters (developed by NASA and MMS) are scheduled to fly on the ARTEMIS satellite in 2000.

In Japan, ion engines developed by Toshiba have flown on the ETS-VI satellite. Despite the problems with orbit injection of this satellite, the units were tested in orbit. The same electric propulsion subsystem was also used on the COMETS satellite.

In conclusion, much basic research on electric propulsion for communications satellites has been completed and the advantages are clear. What remains to be accomplished is to establish a solid track record of the reliability in orbit. As this depends on many engineering and design details, as well as on parts reliability, further design iterations will be necessary in addition to more research and testing, to understand any potential life limiting factors. Nevertheless, it is expected that electric propulsion will see a much wider use in the future of commercial communications satellites.

7.2. Thermal control

Most of the prime dc power on a communications satellite is used by the transmitters in the payload. In today's satellites, the dc to rf efficiency for SSPAs is around 35% and for TWTAs around 50 to 70%. Therefore a substantial part of the dc power is dissipated and must be removed from the spacecraft. In a modern three axis stabilized GEO spacecraft (shaped approximately as a cube) only the north and south facing panels can be used to radiate heat to cold space (they are inclined with respect to the ecliptic at approximately 23 degrees and will receive some solar radiation); all other sides will be exposed directly to the sun at some

time during the day, thus preventing effective heat rejection. The north and south facing panels carry usually a major part of the heat producing payload on the inside and the solar array on the outside. Heat pipes are used by most communications satellites to carry the heat from transmit amplifiers to radiating surfaces and equalize the temperature inside. A new, much lower cost, heat transport system to equalize temperatures between north and south panels has been developed in Europe. Conventional pipes connect two fluid loop exchangers (using a proprietary material) located on the north and south panels respectively. This design avoids bends in conventional grooved heat pipes.

As the satellite prime power increases from 5 to 10 or more kW (see Fig. 1), there is a consensus in the industry that thermal control is a major problem because the radiating surfaces are not increasing correspondingly in size. One solution envisaged by several manufacturers is deployable radiators. Further developments are needed to provide reliable solutions.

Another area of concern is thermal control in on-board processors. These have substantial dissipation; on the order of 500 to 1500 W of heat must be carried away from the inside of a small box and radiated to space. Heat pipes can carry heat from one place to another, however, they are bulky. Processor heat dissipation has become a significant problem in implementing full on-board processing, because the factors involved drive the solution towards a very high heat density (watts/cm³). This problem arises with the use of smaller earth stations and mobile terminals creating bursty traffic. Efficient use of the satellite bandwidth and power led to creation of multiple access control schemes and eventually to the notion of architectures using frequency division multiple access on the uplink with time division access on the downlink. Such an architecture require on board processors with high digital sampling rates and high speed operation. Such processors employ small feature sizes which exacerbates the heat dissipation problem. Digital processors must be cooled so that the junction temperatures of the transistors are 125°C or less for silicon devices. Heat dis-

sipation is proportional to clock speed and operating voltage. Operating voltage has been reduced to 3 V. Clock speeds continue to rise in proportion to increasing data rates per access, and increasing numbers of simultaneous accesses. Consequently, either a more efficient process for heat removal or a different hardware process must be found. The present approach is that of heat removal using specially developed heat pipes. While heat pipes have been used in satellite before to carry heat to radiating cold plates, the device and heat density in the digital processor requires a micro-scale heat pipe. Such a device was recently announced by the European company, AER, and is advertised for sale.

The ultra-flat micro-heat pipe is constructed of thin sheets with grooves engraved on the surface and bonded together. A cooling fluid is introduced under vapor pressure conditions. The device is fabricated as a flat package resembling a chip carrier, and is matched to a particular chip package. Heat is carried away and conducted through a cooling loop to a radiator for removal from the spacecraft. With water as the cooling fluid and copper as the metal, the micro heat-pipe exhibited conductivity 4 to 15 times that of solid copper. The improvement is due to the phase transformation (liquid to vapor) of the cooling fluid. Various coolants (ammonia, etc.) and various metals (stainless steel, aluminum, etc.) can be used. The engraved sheets are 0.1 mm in thickness and can be stacked to create sandwiches from 0.5 mm to several mm. The heat pipe for the TO 254 microelectronics package is 1.2 mm thick, 100 mm long and weighs 0.35 g. It can remove 20 W of heat with only a 10 K temperature gradient over the 200 mm length (from chip mounting surface to heat sink).

In a large GEO mobile satellite development (Hughes), heat dissipation was identified as the most critical challenge. Similarly, in the Japanese 'Gigabit' Ka-band satellite development, this same problem is one of the three most critical issues. Nevertheless, the developments are proceeding and within a few years (i.e., 2003–2006) such satellites with full on-board processing are anticipated.

7.3. Attitude control

Conventional attitude control systems for three axis stabilized spacecraft with earth and Sun sensors, momentum wheels, jets and associated electronics are in production at many manufacturers all over the world. Star trackers (to improve pointing accuracy for large

antennas with very narrow beams) are being developed in the United States and Japan, but are not yet in operational use due to cost and operational complexity. There is engineering work on laser gyros in the United States, with improved versions eventually capable of replacing the conventional type gyros used for attitude sensing.

In the last five years, GPS receivers have been used on satellites to establish location and also attitude. The technology used for these receivers is conventional; only the application is novel.

8. Smaller satellites (LEO and Microsats)

As reported herein, development continues towards producing ever higher power geostationary satellites. As a counterpoint to this trend, the advent of the 'little LEO' and 'big LEO' systems have given rise to many innovations in spacecraft design and manufacturing aimed at producing smaller satellites at lower cost. Motorola and Loral have created special factories for assembling the relatively large number of LEO satellites for Iridium and Globalstar. Manufacturing is treated as an end to end process, designed for efficient flow, continuous process improvement, and significant reduction in incremental testing, while also meeting high reliability goals.

These new concepts are also being applied to GEO satellites for certain applications. An example is Cakrawarta-1, launched in 1997 for Media Citra INDOSTAR, by Orbital Sciences Corp (OSC). Cakrawarta-1, shown in Fig. 22, was developed by CTA prior to its acquisition by OSC.

The Surrey Satellite Research Center is producing UoSat-12 (about 350 kg) for Singapore. It carries charge coupled device cameras with sophisticated on-board image processing (38 m resolution multispectral and 10 m monochromatic resolution), together with both VHF/UHF and L/S-band satellite communications. This satellite will fly in a low (LEO) orbit.

These mini-satellites in the 340 to 680 kg class are produced from technology largely within the envelope defined by large GEO satellites, yet may benefit from weight reduction technology aimed at the larger spacecraft. The mini-satellite will also offer opportunity for new technology, an example being an electric thruster produced at the Surrey Center. Matra Marconi has developed a new mini-satellite bus called LEOSTar.

Microsatellites continue to be flown, with many carrying experiments. The Air Force Phillips Laboratory

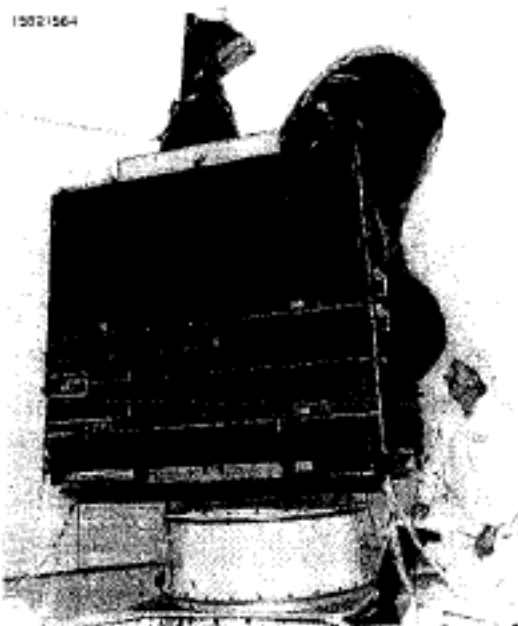


Fig. 22. Cakrawata-1 launched for Media Cita INDOSTAR by Orbital Sciences Corporation.

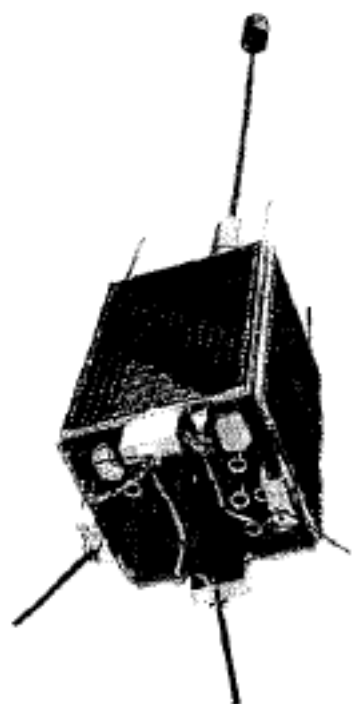


Fig. 23. Surrey Space Center's FASat-Bravo microsatellite for Chile.

plans to fly a series of experimental satellites, some of which may include communications technology experiments. An example of a microsatellite produced by

Surrey Satellite Research Center is shown in Fig. 23. An interesting use of the microsatellite program is to provide an affordable focus for smaller countries to become space faring nations. Such a program, which can also incorporate graduate engineering training at the University of Surrey, has been accomplished with Malaysia, Korea, Singapore, and Spain.

The Orbcomm satellites have been launched into a full constellation of 26 satellites. These microsatellites (~45 kg) provide multiple access with 2400 bps uplinks and 4800 bps downlinks to handheld data terminals. Orbcomm will be the first large scale LEO system with a constellation providing continuous coverage. VITA has operated SateLife store and forward satellites for remote medical consultation since about 1992, when UoSAT-3 was launched. Several additional satellites are now used in this network.

9. Conclusion

There are many challenges in satellite communications ahead, one of them will be to keep the interest in supporting R&D in various necessary disciplines after the current wave of enthusiasm and spectrum allocation for new systems and higher frequencies subsides followed by the disappointing commercial results in some LEO systems. The list of needed technology developments is long, but progress on all fronts is necessary if the longer term future of satellite communications is to be assured. A list of technologies needing long-term R&D attention can be found in [3].

It may be difficult to realize all the potential benefits from the large number ('automobile manufacturing') approach, under financial pressures to go into revenue service as soon as possible. The numbers for satellites are too small to reap statistical benefits from long manufacturing runs. The individual satellites are too expensive to 'throw away' if they are defective or to 'test to death' the first 10% of a satellite production run. Motorola's example of a '6 sigma design & manufacturing' approach must be confronted with the 10% initial failure in orbit that has actually been experienced.

Nevertheless, while there are reasons for caution noted above, the future does look bright. There seems to be no end to the demand for satellite communications services and technology in sight. Sooner or later almost all the developments appear in real systems. There remain very real communications satellite systems applications (like DBS) that will survive and thrive. There is increasing synergy between terrestrial

and satellite systems as each recognizes the advantages of complementary systems. For instance, a concerted R&D effort in Europe is directed towards the transition from GSM to UMTS where satellite links will be integrated seamlessly with terrestrial facilities.

Today there is substantial business and profits in some existing communications satellite systems. For the future, there is no reason why properly designed satellite systems with an appropriate customer basis and a reasonable business plan could not generate an excellent return to the investors.

Acknowledgements

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