Trends in Satellite Communication Technology

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1. Introduction

In 1945, the English science fiction writer and futurist Arthur C. Clarke Published a seminal paper in the journal Wireless World. He showed how three satellites in synchronous orbit could provide global coverage for telephone and television service. Just a year later, the Project Rand group published a serious engineering study of how a man-made satellite could be built. Professor Louis Ridenour, a moving force behind the Rand group in California, proposed a synchronous orbit system as a communication relay. He identified the enormous simplification of earth station design with a stationary satellite and foresaw the development of commercial applications. Apparently, Ridenour was unaware of clarke's work. Unfortunately, the Rand study lay classified for too many years.

In 1955, John Pierce at Bell Telephone Laboratories published a serious analysis of satellite communications. His "Jet Propulsion" paper examined the use of reflecting spheres in 2200 mile orbits as well as active and passive repeaters in synchronous orbit. He concluded that all three might provide broadband, transoceanic communication.

Communication sattelites suddenly becomes an urgent matter and the military took a bold lead. After a few earlier failures, Early Bird, the world's first commercial communictions satellites, owned by the International Telecommunication Satellite Organization(INTELSAT), was launched in Aprie 1965 to provide 240 voice channels between North America and Europe. The satellite was located at the geoshychronous orbit in 35,800 kilometers above the Equator.

Leading trends in the satellite communications field include higher space segment capacity, longer design and orbital maneuver life, increasing diversity in the earth segment (flexibility in beam coverage and connectivity, networking with multiplicity of earth station types), and continuing effort to achieve a higher level of efficiency and economy for commercial and competitive viability under growing requirements and changing telecommunications environment globally. These trends, in turn, have led to an emphasis on technology, techniques and applications primarily based on higher power satellites, smaller

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*이 원고는 본 특집 담당위원이신 최순달교수께서 在美과학자인 고의곤 박사께 청탁, 영문으로 원고를 보내온 바, 필자의 의사를 정확히 전달하고자 번역을 하지 않고 그대로 게재한 것입니다. (편집자 註)

standard earth stations, and maximal compatibility with the evolving integrated networking concepts. Continuing enhancement in the efficiency of the station-keeping operation as well as in the transmission capability, including optimization of the transponder nonlinearity characteristics, is also regarded crucial. Some of the specific technologies and techniques pertaining to thess factors include, for instance, three-axis stabilized satellite design ; ion porpulsion subsystem and inclined orbit operation ; travelling wave tube amplofier(TWTA) linearizer and solid state power amplifiers(SSPAs) ; and applications based on digital transmission with adequate performance using small earth stations.

2. Spacecraft Technology

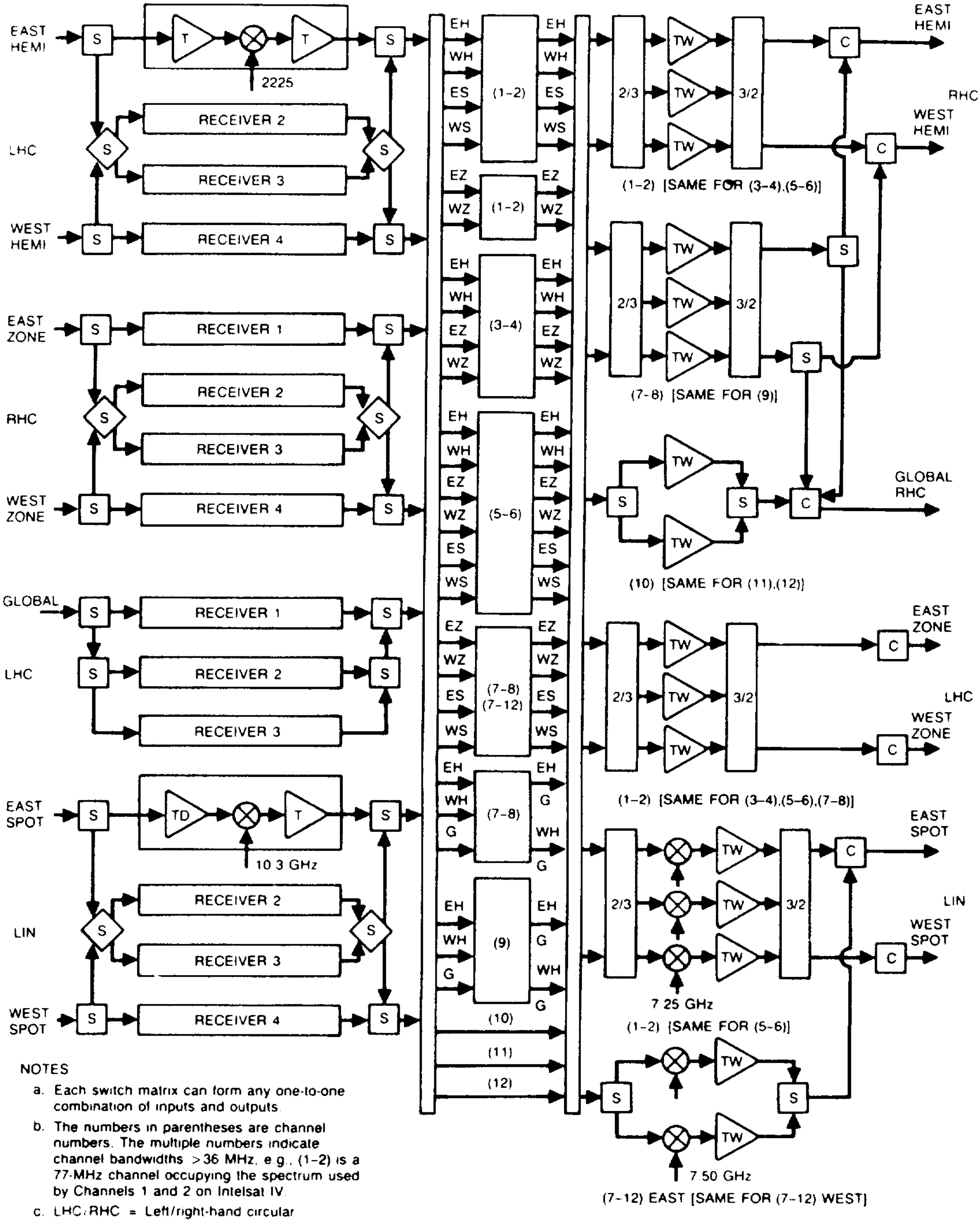
Continuing evolutionary trends in the spacecraft technology area include incorporation of large design life as well as power(e.i.r.p.) and bandwidth, leading to increased capacity and quality while permitting progressive reduction in the earth station size (G/T) and in the overall unit(say, per channel) communication cost. These trends are exemplified by the INTELSAT V, VI, and VII series of satellites [1]. The use of TWTA linearizers in the Ku-Band and of SSPAs in the C-Band in the INTELSAT VII series satellites toward the goal of higher e.i.r.p. and operational optimization (even with smaller dimensions and total bandwidth compared to INTELSAT VI) should be noted.

3. Communications Payload

The stable, earth-oriented attitude of satellites in geostationary orbit allows communications antennas to be highly directional, thereby focussing all the available power on some selected regions of the earth's disc. Therefore, the use of several beams focussing on different regions is allowed. Different beams can use the same frequency band and the same antenna if they are isolated from each other either by spatial separation, or by utilization of orthogonal polarizations. INTELSAT V and INTELSAT VII utilize up to 4 fold re-use of the same frequency band. INTELSAT VI, that was specifically designed in view of the most demanding connectivity role, utilizes 6-fold frequency reuse at c-band.

The design of an antenna is the result of a trade-off among many different considerations. First, obviously, the antennas must fulfill the requirements for links quality, that in to say a sufficient gain to system noise temperature(G/T) at the receiving antenna and a fitted effective isotropic radiated power(e.i.r.p.) at the transmitting antenna. Secondly, antennas must achieved the required beams shapes for each region(earth coverage, hemisphere, zone or spot) which are defined by the needs of satellite's capacities for each region. Moreover, like for every device in a spacecraft, the mass has to be optimized(i.e. minimized in regards of the requirements) in order to fit to the capacity of launchers.

The role of transponder is to transpose the signal's frequency and to amplify the received signal in order to achieve a higher Effective Isotrophic Radiated Power(e.i.r.p.) at the spacecraft transmit antenna interface. Before the microwave signal's conversion, a bandpass filter passes only the uplink frequencies and rejects out-of band signals which would cause degradation in the receiver. Then a low Noise Amplifier(LNA) amplifies the very weak signals so that down-conversion can be achieved without much degradation. After down conversion, another amplifier boosts the signal to a higher level before the various RF channels are demultiplexed into individual channels in the input demultiplexer, often referred as the "input MUX". Each individual channel is now routed to the intended downlink path by the connectivity switch matrix, and amplified by a channel driver(that controls the saturation flux density and gain of the transponder) and a high-powered transmitter(TWTA or SSPA). Then all the outputs are combined together in the output multiplexer and



NOTES

a. Each switch matrix can form any one-to-one combination of inputs and outputs.

b. The numbers in parentheses are channel numbers. The multiple numbers indicate channel bandwidths >36 MHz, e.g., (1-2) is a 77-MHz channel occupying the spectrum used by Channels 1 and 2 on Intelsat IV.

c. LHC/RHC = Left/right-hand circular polarization.
LIN = Linear polarization.

d. Channels (7-8) and (9) may each be used on both EH and WH, or on global.

e. Spot beam antennas have diplexers (not shown).

f. Combiners after transmitters also have inputs from unillustrated transmitters.

g. Spot beam receiver first stage is TD for satellites 1 to 5, T for satellites 7 to 9.

Fig. 1. INTELSAT V communication subsystem.

then transmitted to the antenna interface.

The earlier satellites used C-band repeaters operating 6 GH$_z$ and 4 GH$_z$. The INTELSAT IV-A type satellites utilized spatial isolation techniques to increase channel capacity. The improved INTELSAT IV-A satellites could provide 6000 two-way voice circuits plus two transponders for SPADE and TV transmissions. It has five communication antennas : global receive and transmit, spot beam receive, and two spot beam transmit. The new antennas and transponders, allow an increase to 20 36-MH$_z$ channels from the 12 on INTELSAT IV.

The INTELSAT V satellites[1-6] have two new design features that require significant ground terminal changes. The first feature is the use of dual polarization uplinks and downlinks in the 4-and 6-GH$_z$ bands. All provious Intelsat satellites used one polarization for uplinks and the orthogonal polarization for downlinks. This change requires improvements as all ground terminals to ensure isolation between the two polarizations. The dual polarizations are combined with the two independent beams (east and west) introduced on INTELSAT IV-A. Together, these techniques triple the satellite capacity in the 4-and 6-GH$_z$ bands, compared with the INTELSAT IV design. The second new feature is the use of the 11-and 14-GH$_z$ bands, and two independent beams are used with these bands also.

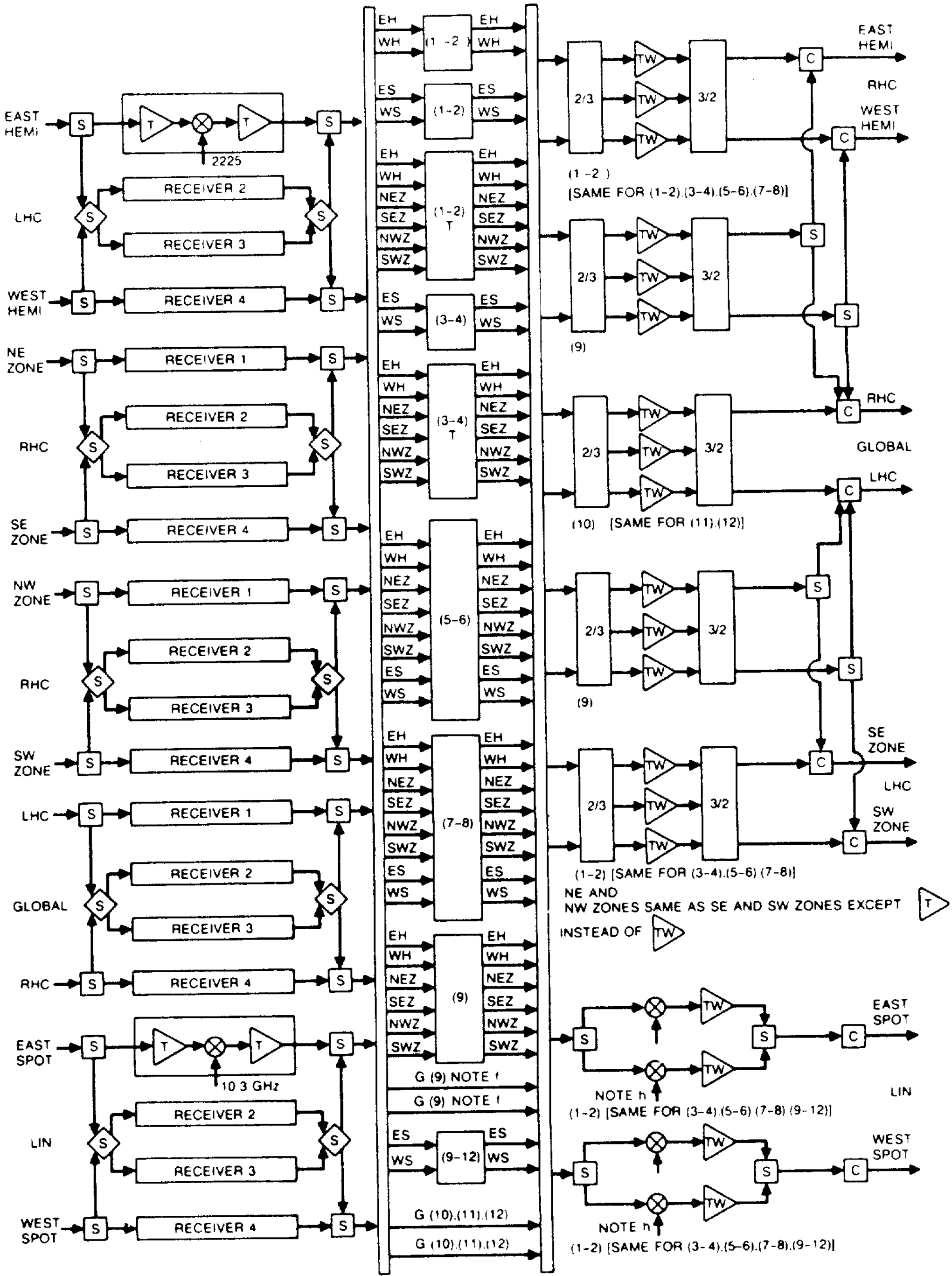
The communication subsystem operates at the 4-and 6-GH$_z$ frequencies used by all previous Intelsat satellites as well as at 11 and 14 GH$_z$. The 4-and 6-GH$_z$ bands have 21 transponders, 16 with 72-or 77-MH$_z$ bandwidths and five with 36-or 41-MH$_z$ bandwidths. The 16 wider transponders are operated with fourfold frequency reuse ; there are four separate frequencies, each with four transponders. Within each co-frequency set, two transponders are assigned to west beams and two to east beams. Thus, these transponder pairs are kept independent by the angular separation of the beams-the same technique used on INTELSAT IV-A. The pairs that share a common and direction are kept independent by the assignment of one to a hemispheric beam and one to a smaller zone beam. These beams are separated, not by direction, but by orthogonal polarizations.

Fig 1 shows the INTELSAT V communication system block diagram. The significant technical development in INTELSAT V system is to introduce. Time Division Multiple Access (TDMA) system with 120 Mbps/QPSK carrier in single transponder. In opting for the introduction of TDMA, INTELSAT recognized the following primary technical and operational advantages of TDMA/DSI techniques :

(a) single carrier-per-transponder time-domain multiple access operation
(b) potential for time-domain processing and, later, for on-board satellite switching
(c) virtual doubling of satellite capacity by speech interpolation of voice telephony circuits.

This new INTELSAT TDMA network opened new era of digital communication equipment, TDMA terminal, Reference Station equipment, TDMA system monitor equipments. Moreover INTELSAT had a challange to bring all together in one operational network. After initial difficulty, the INTELSAT TDMA network has well settled down to full operation as it planned. The INTELSAT V satellite is designed to accomodate TDMA system requirements.

Desire of higher capacity satellites using new or improved technologies encouraged innovation in communication payload area. The major technologies considered were increased frequency rense (using spatial isolation and cross polarization), use of newly allocated portions of spectrum, adjacent to existing 6/4 GH$_z$ and 14/11 GH$_z$ hands, on board microwave switching and increased satellite power. With all these features, the heaviest commercial satellite at 4000 lbs in orbit, the INTELSAT VI satellite [7-12], was designed and manufactured by Hughes and the first satellite was lanunched on Nov. 1989. The communication subsystem block diagram is shown in Fig 2.



NOTES

a. The numbers in parentheses are channel numbers. The mulitple numbers indicate channel bandwidths >36 MHz, e.g., (1-2) is a channel occupying the spectrum used by Channels 1 and 2 on Intelsat IV

b. (1 -2) occupies the spectrum just below (1-2)

c. Each switch matrix can form any one-to-one combination of inputs and outputs

d. The switch matrices marked "T" can be used for SS/TDMA

e. LHC/RHC = Left/right-hand circular polarization
LIN = Linear polarization

f. Channel 9 may be used on both EH and WH or on the co-polarized global beam. It may also be used in all 4 zones or on the co-polarized global beam

g. Spot beam antennas have 11/14 GHz diplexers (not shown)

h. 7 25 GHz for (1-2), (3-4), (5-6)
7 50 GHz for (7-8), (9-12)

i. Combiners after transmitters also have inputs from unillustrated transmitters

Fig. 2. INTELSAT VI communication subsystem.

The global coverage transmission and reception beams each have a dual polarized horn. The largest deployed reflector produces six 4-GH$_Z$ transmit beams. The second deployed reflector provides the corresponding 6-GH$_Z$ receive beams. Two of the beams provide east and west hemispheric coverage. They share a common polarization and frequency plan, their signals kept separate by the directions of the two beams. The other four are zone beams. They use the same frequencies as the hemispheric beams but the opposite polarization. The four are separated from each other by their directions, which are nominally northeast, northwest, southeast, and southwest. The southern zone beams are larger than the nothern zone beams because they serve population centers in the equatorial and southern parts of the globe, which are more dispersed than those in the northern part of the globe. The hemispheric beam patterns are fixed, but the zone beams have three patterns, one for each ocean region, which can be switched in orbit. The two smaller reflectors provide steerable east and west spot beams for 11 GH$_Z$ transmission and 14 GH$_Z$ reception.

The switch matrices in the center column of the communication subsystem diagram allow many different inerconnections between the various beams. This flexibility allows the satellite to be in a configuration that is best suited to the traffic pattern that it is handling. Most of the switch matrices are changed infrequently by ground command. Two may be switched, according to a ground controllable pattern stored on the satellite, through several states within a 2-msec frame. This capability will be used in a satellite-switched TDMA(SS/TDMA) mode, which will significantly increase the satellite's capacity relative to FDMA operation[8,11], relative to FDMA operation[8, 11].

Development of the satellites started in March 1982. Critical new technology feasibility had been proved earlier through several studies sponsored by Intelsat and others.

The most recnt INTELSAT VII series satellites was awarded to Ford Aerospace Corporation(FAC) in October 1988 and scheduled to launch in Nov. 1991. The INTELSAT VII satellite is a three axis stabilized, multiple frequency band communication payload spacecraft with a 10.9 year design lifetime. Fig. 3 shows the INTELSAT VII on-orbit configuration.

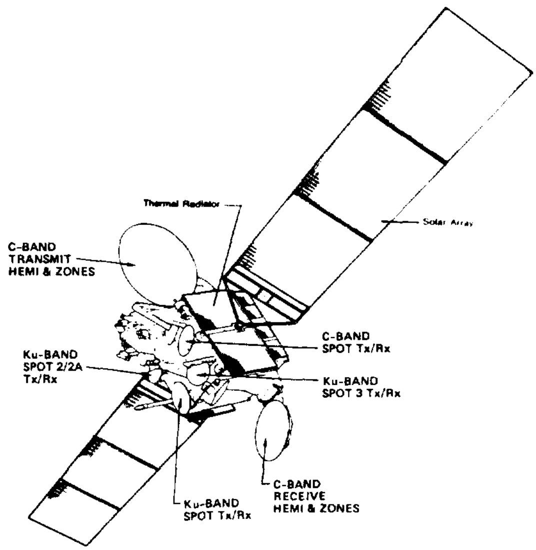


Fig. 3. INTELSAT VII Satellite

The INTELSAT VII spacecraft is specified with a few advanced payload and bus technologies while designed with constraints to replace INTELSAT V A spacecraft.

3.1 C-Band Global/C-Spot coverages switchability

A unique feature of INTELSAT satellites is a C-band global coverage antenna that allows straightforward interconnection of small users all across the world, and is also essential to allow occasional use Television transmission from anywhere to anywhere.

The INTELSAT VII C-Spot will provide very high RF performance both for the up-link and the downlink, will be independently steerable, and will allow to allocate as needed the six "Global/C-Spot" transponders to be Global beam or the C-Spot beam on a channel-per-channel basis. The "C-Spot mode of operation" provides a 7dB advantage in both G/T and e.i.r.p. over the "Global mode of operation". This flexibility is expected to lead to optimal utilization of these transponders at all orbital locations.

3.2 Long In-Orbit Life

The redundancy and reliability of INTELSAT VII provides and orbital design life of 10.9 years. But the large bipropellant tanks will provide an actual inorbit maneuver life in the order of 12.5 years (guaranteed) to 14.5 years(typical) with Atlas IIAS, and of 19 years (guaranteed) with Ariane 44LP. In addition, the satellite will be equipped with an inclined-orbit coverage distortion compensation capability that would allow if necessary continued provision of some service for up to four years after bipropellant tanks depletion to earth stations equipped with satellite tracking capability.

3.3 Easier and More Secure Sattellite Control

INTELSAT VII will include a Spacecraft Control Electronics (SCE) equippment using microprocessors that will be a genuine electronic brain. In addition to conventional commanding and telemetry, the SCE will allow block commands(execution of a series of commands pre-loaded in the satellite), time-tag commands (excution at the right time, under control of an on-board clock, of pre-loaded commands) and autonomous commands for "housekeeping" functions (firmware loaded in Read-only Memory ROM). As a result, autonomous operation of the satellite for a period of up to 21 days is possible.

3.4 K-band Spot Coverage

INTELSAT VII includes a narrow elliptical Spot 1 coverage identical to the INTELSAT V & VI East Spot, a broad elliptical Spot 2 coverage (West Spot) that can be extended in the POR by activation of a S2 + S2A mode (insertion of a switchable coupler) to the Spot 2 coverage, and a third circular Spot 3 coverage to which unused transponders of either the Spot 1 or the Spot 2 or a combination of both can be assigned. Like for the Zone transponders, the secret of this highly flexible K-band transponders allocation is the association of a three-fold frequency re-use K-band antenna configuration with a 2-fold frequency re-use K-band transponder configuration. This approach provides considerable flexibility for adjusting the satellite configuration to actual traffic patterns. Fig. 4 provides representative examples of possible K-band coverages.

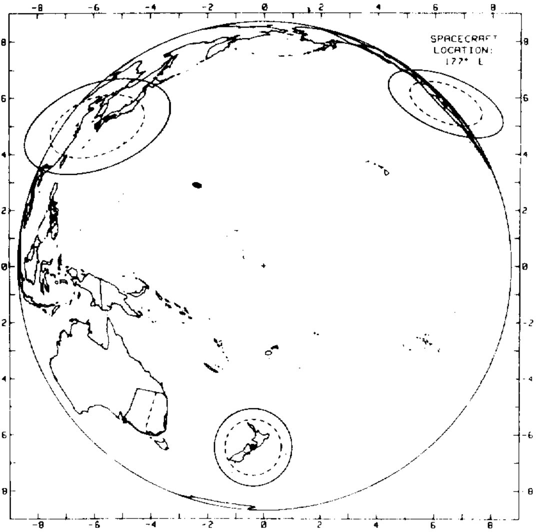


Fig. 4. INTELSAT VII K-Spot Coverage

Fig. 5 is shown as illustrative purpose. This K-band repeater block diagram illustrates the flexible allocation of transponders between Spot 1, and Spot 2 and Spot 3 by means of three sets of identical IMUXes and by means of three OMUXes. Unfortunately, shortage of mounting space did not allow utilization of three sets of identical ll-channel K-band OMUXes. As a result, only the Spot 3 can utilize TWTAs of either power (50 W or 35 W) in any of the three switchable frequency bands (10. 95

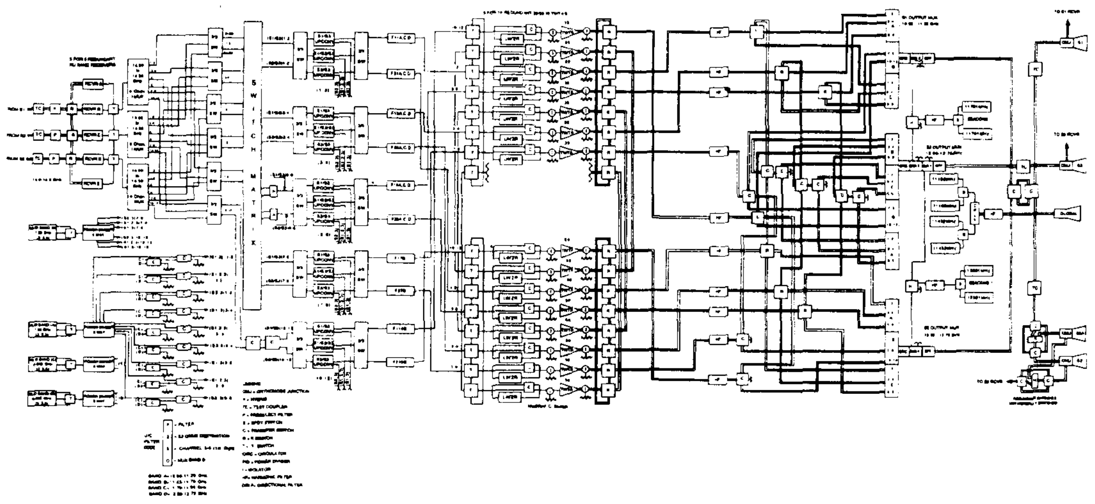


Fig. 5. IS-VII Ku-Band Block Diagram

-11.2 GH_Z, 11.7-11.95 GH_Z, or 12.5-12.75 GH_Z).

3.5 Advanced Technologies

Efforts are being devoted to advancing spacecraft and earth station technologies in order to secure that future satellites will maintain their role of preeminence in long distance communications. Major efforts are directed toward the following goals:

1) Utilization of digital modulation and coding technigues with higher spectrum and power efficiency ·
2) Digital and analog compression techniques in source coding
3) Higher e.i.r.p. spacecraft with enhanced antenna reconfigurability
4) On-boare processing technique including bit regeneration, demodulation/remodulation, demultiplexing/remultiplexing [13]
5) Ka-band (30/20 GH_Z) frequency utilization [14-16]
6) Inter-satellite links (ISL) using microwave or optical wavelengths

In this paper discussion will bedevoted to advance spacecraft technologies. Higher spacecraft e.i.r.p. may be achieved by increasing either the TWTA output power or the antenna gain. Limitations are dictated by the spacecraft prime power, the antenna mass and volume and the complex coverage ares.

3.6 Multi-beam Antennas and MMIC Technologies

Multi-beam architectures offer the possibility of centering beams on traffic nodes and reusing frequency bands several times, thus achieving a very efficient utilization of spacecraft and spectrum resources. Furthermore Spot beams may be scanned over traffic sources with dwell times tailored to local traffic demand. Under these circumstances users are catered for by a small number of time shared beams rather than by a large number of fixed beams. In the past, antenna hardware complexity required by many traffic nodes scattered over an area as large as the continental US (CONUS) was beyond technological feasibility. Recently new technologies have emerged that make scanning and multi-beam antennas very attractive[13, 14]. Technology demonstrators have been built featuring dual reflector optics with focal feed arrays. Advanced variable power dividers and phase shifters were developed for high scanning efficiency. Based on the experience gained within these programs a scanning beam antenna is currently being built for NASA[14].

Presently spacecraft scanning multi-beam antennas are beginning to benefit from the progress made in radiation resistent GaAs Monolithic Microwave Integrated Circuit (MMIC) technologies[16]. The replacement of ferrite technologies by GaAs modules in active phased arrays promises to reduce weight and power consumption, increase the scanning speed and introduce dynamic control of phase and amplitude weighting. The cost effectiveness of the GaAs technology insertion into scanning beam antennas is primarily dependent upon the cost of the individual modules which must perform at high levels of power added efficiency and, for multi-carrier operation, linearity.

3.7 On-Board Processing

When the earth segment consists of a large number of small terminals, it may be cost effective to increase the signal processing capabilities on board the spacecraft in order to still be able to provide quality services in a mesh network of small earth stations. In particular on-board signal processing may be regenerative, namely involve demodulation and modulation with access to the baseband data. Baseband date processing is mandatory in system configurations with different uplink and downlink modulation, coding or multiplexing formats. For example, in the presence of a large number of small earth stations it may be convenient to have a multicarrier uplink and a single carrier downlink. In fact, multicarrier uplinks reduce the termianl e.i.r.p. requirements while single carrier downlink allows the on-board TWTA to operate close to saturation in a high efficiency mode.

On-board FDMA multicarrier demodulators do not have the burden of fast clock and carrier acquisition but must demodulate a multiplicity of synchronous digital channels in a power efficient way. The problem is mainly technological. Hardware implementations for commercial applications are lagging. The main reason is that on-board MCD's are not procticaliy feasible unless high speed, low power, radiation hardened digital IC technologies are available for A/D conversion, FFT, and filtering.

3.8 Solid State Power Amplifiers (SSPA)

Solid State Power Amplifiers on-board commercial satellites provides the benefits of increased linearity for a given output power and enhanced reliability. In fact elimination of cathode life limitations and high voltage power supply complexities greatly increases the probability that each power amplifier and survive the satellite mission. The increased mass of the prime power source due to a lower power added efficiency is more than offset by the power source due to a lower power added efficiency is more than offset by the smaller mass of the SSPA compared to that of the TWTA. Today an "all SSPA" solution for a C-band payload may lead up to 20% mass savings if redundancy schemes which use shared DC-DC converters are adopted. RCA Satcom 5 flew the first SSPA in 1982. The power output was 8.5W and the power added efficiency was 29%.

Recently substantial improvements in output power capability have been made In C-band and Ku-band SSPA's mainly due to the availability of high efficiency internally matched power GaAs MESFETs. INTELSAT VII spacecraft is designed with all the SSPAs of up to 30W at C-band Hemi/Zone coverage transponders

Most of the advaced technologies mentiond are utilied in the Advanced Communications Technology Satellited (ACTS) by NASA. The goal of this high risk and the most advanced communication program is to enable growth in channel capacity and effective use of the frequency spectrum.

Key technologies to be validated as part of the ACTS Program include the multibeam antenna, a rapidly reconfigurable hopping and fixed spot beam antenna to serve users equipped with small-aperture terminals on their premises; the baseband processor, a high-speed digital spacecraft switch to efficiently use transponder capacity (in time and frequency) for routing individual circuitswitched messages; the microwave switch matrix, a dynamic reconfigurable switch to route high-volume point-to-multipoint traffic; rain fade compensationtechniques such as forward error correction and power control to automatically overcome uplink and downlink signal level changes; and Ka-band components, the development of both flight and ground terminal hardware at 20 and 30 GH_z.

4. SUMMARY AND CONCLUSIONS

In this paper some of the important trends in the spacecraft technology development have been discussed. Trends of higher satellite radiate power, which involves higher TWTA powers and antenna reconfiguration, and Ka-band (30/20 GH_z) utilization are discussed.

Evolutionary trends in satellite communications in general have demonstrated immense potential for meeting the evolving nees and challenges regarding provision of global telecommunications during over past two decades. Their promise for the coming decades as we enter the 21st century may far surpass our imagination.

The expansion of fixed satellite service market will depend upon more inelligent spacecraft and a network of more cost effective small earth stations. Radiation hardened microwave analog technologies and high speed digital technologies are getting ready to meet the challenge posed by future markets. At present commercial satellite communications are going through a trasition period.

REFERENCES

[1] J. Alper and J. N. Pelton, eds., The Intelsat Global System, Progress in Astronautics and Aeronautics, Vol. 93, AIAA, New York (1984).

[2] E. A. Robertson, "Planning for the Intelsat V System," National Telecommunications Conference: NTC '74 (December 1974).

[3] R. J. Rusch, J. T. Johnson, and W. Baer, "Intelsat V Spacecraft Design Summary," Paper 78-528, AIAA 7th Communications Satellite Systems conference (April 1978).

[4] G. T. Hayes, N. T. Totah, and J. W. Young, "Design of the Antenna Module Structure for Intelsat V Spacecraft," Paper 78-592, AIAA 7th Communications Satellite Systems Conference (April 1978).

[5] J. L. Dicks and M. P. Brown, "Intelsat V Satellite Transmission Design," Paper 2.2, International Conference on Communications: ICC '78(June 1978).

[6] J. C. Fuenzalida, P. Rivalan, and H. J. Weiss, "Summary of the Intelsat V Communications Performance Specifications," Comsat Technical Review, Vol. 7, No.1 (Spring 1977).

[7] G. P. Cantarella and P. Nadkarni, "Intelsat VI Spacecraft Concepts," International Telemetering Conference Proceedings (November 1980).

[8] R. Colby, G. Forcina, and B. A. Pontano, "SS/TDMA Operation Using Intelsat VI Spacecraft," Paper F7. 2, National Telecommunications Conference: NTC '81 (December 1981)

[9] S. B. Bennett and D. J. Braverman, "Intelsat VI Technology," IAF-82-68, 33rd Congress of the international Astronautical Federation (September 1982).

[10] A. Ghais et al., "Summary of Intelsat VI Communications Performance Specifications," Comsat Technical Review, Vol. 12, No. 2 (Fall 1982).

[11] G. Forcina and B. Pontano, "Fault Detection/Diagnostics for the Intelsat VI SS-TDMA subsystem," Sixth International Conference on Digital Satellite Communications (September 1983).

[12] M. F. Caulfield, S. O. Lane, and F. A. Taormina, "Intelsat VI Antenna System," Paper 47.6, Global Telecommunications Conference: Globecom '83 (November 1983).

[13] "Spacecraft Multibeam Antenna System for 30/20 GH_z" FACC, Final Report WDL-TR 10138 for NASA contract NAS3-22498, Jan 10, 1984.

[14] C. C. Chen and W. A. Minnin, "Advanced 30/20 GH_z Multibeam Antenna for Future Communications Satellites" 1983, pp. 95-102.

[15] Y. H. Choung and W. C. Wong, "Multibeam Antenna Design and Development for NASA Advanced Communications Technology Satellite (ACTS)", Proc. 1986 IEEE Global Telecommunication Conference, Houston, TX., Dec. 1, 1986, pp. 1. 6. 1. 1-1. 6. 1. 9.

[16] G. Anzic et al., "microwave Monolithic Integrated Circuit Development for Future Spaceborne Phased Array Antennas" Proc. AIAA 10th CSSC, Orlando, FL, March 1984, pp. 43-53.