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FOREIGN APPLIED SCIENCES ASSESSMENT CENTER
TECHNICAL ASSESSMENT REPORT

SOVIET SATELLITE COMMUNICATIONS SCIENCE AND TECHNOLOGY

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August 1991

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ABSTRACT

This report represents the contributions and consensus of six US scientists and engineers concerning the current state of the art and projections of future Soviet satellite communications technologies. The panel members are experts in satellite stabilization, spacecraft environments, space power generation, launch systems, spacecraft communications sciences and technologies, onboard processing, ground stations, and other technologies that impact communications. The panel assessed the Soviet ability to support high-data-rate space missions at 128 Mbps by evaluating current and projected Soviet satellite communications technologies. A variety of space missions were considered, including Earth-to-Earth communications via satellites in geostationary or highly elliptical orbits, those missions that require space-to-Earth communications via a direct path and those missions that require space-to-Earth communications via a relay satellite.

Soviet satellite communications capability, in most cases, is 10 years behind that of the United States and other industrialized nations such as Japan, Italy, and France. However, based upon an analysis of communications links needed to support these missions using current Soviet capabilities, it is well within the current Soviet technology to support certain space missions outlined above at rates of 128 Mbps or higher, although the published literature clearly shows that the Soviet Union has not exceeded 60 Mbps in its current space system. These analyses are necessary but not sufficient to determine mission data rates, and other technologies such as onboard processing and storage could limit the mission data rate well below that which could actually be supported via the communications links. Presently, the Soviet Union appears to be content with data rates in the low-Earth-orbit relay via geostationary mode of 12 Mbps. This limit is a direct result of power amplifier limits, spacecraft antenna size, and the utilization of K_u -band frequencies.

In response to decreased governmental support, the Soviet communications satellite industry is showing signs of some internal competition, is working on increasing communications satellite lifetime, and is also striving to develop joint ventures with Western firms. The joint ventures (attractive to the Western partners because of the Soviet launch capabilities) are likely to provide the Soviets much improved access to Western (and Japanese) technology.

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SOVIET SATELLITE COMMUNICATIONS SCIENCE AND TECHNOLOGY

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FOREWORD

This report, *Soviet Satellite Communications Science and Technology*, is one in a series of technical assessment reports produced by the Foreign Applied Sciences Assessment Center (FASAC), operated for the Federal government by Science Applications International Corporation (SAIC). These reports assess selected fields of foreign (principally Soviet) basic and applied research, evaluate and compare the foreign state of the art with that of the United States and of the West in general, and identify important trends that could lead to future applications of military, economic, or political importance. This report, like others produced by the Center, is intended to enhance US knowledge of foreign applied science activities and trends to help reduce the risk of technology transfer and also to provide a background for US research and development decisions. Appendix F is a list of titles of FASAC reports completed and in production.

This report was prepared by a panel of nationally recognized scientists and engineers who were chosen on the basis of their background in military and commercial satellite communications science and technology:

- Dr. J. Neil Birch
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Birch Associates, Inc.
- Dr. S. Joseph Campanella Vice President and Chief Scientist
COMSAT Laboratories
- Dr. Gary D. Gordon Independent Consultant
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- Mr. Wilbur L. Pritchard President
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- Mr. Reinhard Stamminger President
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On a part-time basis, over the period December 1989 to November 1990, each panel member devoted a substantial amount of time toward assessing the Soviet published research literature on current and future Soviet satellite communications science and technology. The assessment covers:

- satellite stabilization and environment,
- communications satellite payload technology, including modulation and coding,
- power generation on spacecraft,
- Earth terminals and associated equipment,
- analog-to-digital converters, storage, and image processing.

As a direct result of the changes that are occurring in the Soviet Union, the panel was able to read the latest Soviet publications and take advantage of symposia and major conventions at which Soviet researchers are openly displaying and discussing their latest space technologies. The principal Soviet technical periodicals reviewed by the panelists are listed in Appendix E.

EXECUTIVE SUMMARY

Satellite communications technology is a broad subject in that the ability to communicate to, from, and through a satellite is determined by a variety of other related technologies. Therefore, in order to assess the current Soviet satellite communications technologies and to project the future of these technologies, it is necessary to evaluate and project a myriad of other technologies that impact on communications. It is not sufficient to investigate satellite communications payload technologies without comparable evaluations of spacecraft stabilization, space power generation, launch systems, ground stations, communications payloads, and onboard processing.

As in the United States, the Soviet literature specifically related to communications to, from, and through satellites is heavily concentrated on communications satellites. While this report represents a strenuous effort to focus on the underlying satellite communications technologies, most of the information available to the panel came from published Soviet sources concerned with communications satellites.

The one bright spot in Soviet satellite communications science and technology is the ability to lift heavy payloads into low-, medium-, and geostationary Earth orbits, easing the constraints on satellite design. Over the years, the Soviet Union has developed a line of very reliable expendable boosters, for example, Proton, Zenit, and, more recently, Energiya, a heavy lift rocket that, while impressive, has limited utility. It is expected that the Soviet Union will attempt to develop a smaller version of the Energiya. This vehicle could find a large market at very competitive launch costs.

Soviet spacecraft, in general, are crude but effective. Soviet spacecraft designers have not employed the elegant solutions to spacecraft problems used in the West and Japan. Soviet communications satellites are heavy in terms of total-weight to useful-payload-weight ratios. This apparently is due to a lack of technology and an abundance of lift capacity.

Soviet communications satellites are not over-designed in terms of their reliability limits. Mean mission durations for Soviet communications satellites

are on the order of three years, while mean mission durations for equivalent Western and Japanese missions are typically 10 years. Soviet spacecraft designers apparently recognize the weakest subsystem, and if this subsystem reliability cannot be improved, other subsystems are designed accordingly.

Spacecraft stabilization techniques currently employed by Soviet designers have been adequate for existing missions. However, the published literature did not reveal any real technology that addresses precision spacecraft stabilization or precision antenna pointing required to close high data rate links (for example, from a low-altitude spacecraft through a relay satellite to a ground facility). This apparent lack of satellite antenna technology could prove to be a factor limiting high data rates for future missions. The United States has, for several years, transmitted 300 Mbps from low-altitude spacecraft through its Tracking and Data Relay Satellite via highly directional tracking antennas at K_u-band (15 GHz).

The Soviet ability to generate primary power in space is very respectable. They have deployed large solar arrays on a number of missions, and their primary electrical power generation on geostationary communications satellites is on a par with that of the West and Japan. While Soviet electrical power generation is on a par, their solar array appears to have an efficiency of 70 percent that of the US solar array, and the watts-per-pound ratio is significantly less than that of the United States. These inefficiencies, however, have not had an adverse effect on Soviet space missions to date.

The Soviet Union has pioneered high-power nuclear sources in space. The Topaz electrical power generation module is advertised as a 10-kW power source. The United States is considering buying a Topaz to determine if it can be redesigned for US missions.

Soviet energy storage batteries on spacecraft are conventional and generally procured from outside the Soviet Union. The Soviet literature did not reveal any advanced technologies in fuel cells or more modern high-energy-density batteries found in the West or Japan.

Soviet communications satellite technology is lagging that of the West and Japan. The Soviet Union appears to be limited to communications data rates of

60 megabits per second (Mbps) or less, although it has access to commercial technology that operates to 120 Mbps (INTELSAT). The 60-Mbps rates have been demonstrated over the Intersputnik satellite telecommunications network serving the Soviet Union and certain former allies. Talks are underway that could result in the integration of Intersputnik with the INTELSAT community. If this occurs, additional communications technologies that support high data rates could be available to the Soviet Union.

The Soviet Union is becoming more dependent on geostationary communications satellites. By the early 2000s, the Soviet Union is expected to employ approximately 300,000 voice channels over domestic geostationary satellites. These satellites are likely to be C-band and K_u-band satellites derived from INTELSAT technologies, and they will be capable of 120 Mbps per satellite transponder. Current Soviet communications satellites have a limited number of transponders that can handle up to 60 Mbps per transponder. A typical satellite has eight transponders for a total capacity of 480 Mbps. Typical US communications satellites have at least 24 transponders and up to 120 Mbps per transponder. US capacities per satellite exceed Soviet satellite capacities by a factor of six.

Calculations by the panel led to the conclusion that the Soviet Union can transmit at least 128 Mbps from space missions in Earth orbit directly to ground facilities. Given no other limitations, the Soviet Union could transmit rates equal to or greater than 128 Mbps through an appropriately designed satellite such as the US Tracking and Data Relay Satellite system. This could be accomplished with the paralleling of 60-Mbps channels in a frequency division multiplexing scheme based on current technologies. However, based upon currently documented Soviet capabilities, we have shown that relay satellite data rates should not exceed 12 Mbps. This limit is based on current TWTA (traveling wave tube amplifier) power levels, frequencies, and antenna sizes employed.

The Soviet Union also appears to be data-rate-limited on transmission capability complementary to satellites. The upper bound on line-of-sight (ground-based) microwave transmission rates currently in use in the Soviet Union is 32 Mbps. This modest rate of 32 Mbps on longhaul microwave is low by Western and Japanese standards, which typically operate at 135 Mbps to rates as high as 512 Mbps.

With the possible relaxation of COCOM restrictions and joint ventures between the Soviet Union and other enterprises, the Soviet Union may acquire certain critical technologies that could increase its communications capabilities over satellites, from space and through relay satellites. Critical technologies include solid-state low-noise amplifiers, advanced multi-beam satellite antennas, onboard solid-state processing and switching subsystems, and onboard imagery processing (including more storage/recording devices and high-speed microcircuit logic technology for higher-speed modems).

For nearly 20 years, the Soviet Union has been publishing extensively on spread spectrum communications, and Soviet researchers understand the threats to communications from interference and nuclear effects. Therefore, with respect to military-specific missions, it appears that the Soviet military will increase its dependency on satellite communications for its strategic and general-purpose forces (this speculation is based on the Soviet desire for highly mobile forces and survivable strategic forces). The Soviet Union may be expected to use spread spectrum signals for critical military satellite links. It may also be expected to employ frequency hop spread spectrum techniques to support strategic forces, since frequency hop techniques are considered the best approach to counter nuclear scintillation propagation effects. The characteristics of these frequency hop transmissions should follow signal designs appropriate for time dispersive fading channels.

Communications links from a low-Earth-orbit satellite through a geostationary relay satellite can be limited by onboard processing and storage. Tape recorders can be used as onboard storage. US spaceborne recorders can operate at rates equal to or greater than 30 Mbps with several hours of record time. It is doubtful that the Soviet Union has highly reliable tape recorders that can operate near these speeds or for these durations. Therefore, it is suspected that current Soviet recorders could be a factor limiting data rates.

US industry has developed solid-state mass storage for spacecraft that can store 2 gigabytes of data and play back these data at rates up to 140 Mbps. The Soviet capability in solid-state spacecraft recorders/playback is unknown, although France has supplied the Soviet Union with modest solid-state onboard

storage. Given the Soviet lack of advanced solid-state microcircuit technologies, it is believed that the Soviet Union has no meaningful solid-state onboard high-speed mass storage capabilities of its own.

Given the current economic and political situation in the Soviet Union, it is expected that the entire Soviet space program is under review and is likely to be scaled down. Since the space effort is very important to the Soviet Union, the Soviets are likely to be very aggressive in joint ventures with the West and Japan. Thus, the future of Soviet space communications technology depends, to a large extent, on the degree of cooperation extended to the Soviet Union by the industrialized nations. Major Soviet contributions to joint ventures would be reliable launch vehicles. Soviet satellite communications technologies can be significantly improved through these ventures, and target ventures will focus on current Soviet deficiencies that appear to be:

- solid-state power amplifiers;
- advanced antenna designs and fabrications for spacecraft;
- high-speed logic and high-speed analog-to-digital converters;
- spacecraft storage and advanced digital signal processing for onboard applications;
- longer endurance primary and secondary spacecraft power systems; and
- communications technologies at frequencies above 14 GHz.

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CHAPTER I ASSESSMENTS

A. INTRODUCTION

This chapter provides concise assessments of those key Soviet satellite and Earth station technologies that impact on current and future Soviet satellite communications capabilities:

- satellite stabilization and environment on spacecraft;
- communications satellite payload technology;
- power generation on spacecraft;
- Earth terminal research;
- analog-to-digital conversion, storage, and image processing; and
- digital signal processing and high-speed logic.

Relevant Soviet technology is examined to assess Soviet limitations in satellite communications. Soviet technological capabilities required to build satellite-based communications systems for their current needs are adequate. Currently, the maximum information transmission rate from a single transponder on a Soviet/Intersputnik communications satellite is 60 megabits per second (Mbps) over a 36-megahertz (MHz) bandwidth, but there is no obvious barrier to Soviet development of systems with higher bit rates.

Most Soviet subsystems are simpler and heavier than comparable ones built in the West. While the Soviet Union lags behind the West and Japan in several technological areas, none of these should limit the Soviet communications capability, since the Soviet Union has the necessary launch capability to trade on-orbit mass for higher technology, lower power, lighter weight designs.

A few general observations apply to all fields of Soviet spacecraft technology: Soviet researchers probably have not been exposed, in detail, to Western spacecraft technology, and their solutions are likely to have evolved using different methods, which are equally valid. In the West, "better" often means a smaller mass, but the Soviet Union has used simpler, more massive solutions in many

areas, which are otherwise equally effective. In areas where the West has made extensive use of computers, the Soviet Union is years behind.

B. SATELLITE STABILIZATION AND ENVIRONMENT ON SPACECRAFT

The conclusions on the technological level of various subsystems related to communications satellite stabilization and environmental control are as follows:

- Soviet three-axis spacecraft stabilization techniques are sound and perform properly, but Soviet stabilization control systems are well behind those of the West. This deficiency, however, is not a current barrier to satellite communications.
- On the use of orbits and small stationkeeping thrusters, the Soviet Union is on a par with the West. Soviet workers show a good understanding of the geostationary orbit, and are the authority on the 12-hour elliptic Molniya orbit. Some references to electric-chemical propulsion indicate that the Soviet Union is pursuing lines similar to those of the West.
- On spacecraft thermal control, the Soviet Union is lagging the West in predicting spacecraft temperatures, but again, this limitation is not a barrier to satellite communications at higher data rates.
- With no sophisticated computer-controlled shakers, and no references to thermal-vacuum tests, testing of Soviet satellites, especially communications satellites, is behind such work in the West. This could be a limitation on satellite communications as a result of poorer reliability and on-orbit lifetime.

No concerns or surprises are likely to develop in the next five years. The Soviet Union undoubtedly will build and launch new satellites for/with communications, using fundamental spacecraft technology. Two developments are important to Soviet progress in spacecraft technology:

- Mass reductions will result both from learning from the West and Japan and from a more competitive environment. In the West, competitive bidding tends to be a factor in the building of satellites, and this drives the design to a lower mass.
- The widespread use of computers will have a significant effect on stabilization control, spacecraft testing, and thermal modeling. The speed with which these changes will take place depends greatly on the continuation of recent political trends.

C. SATELLITE COMMUNICATIONS PAYLOAD TECHNOLOGY

Conclusions drawn from an extensive review of Soviet civil and military satellite communications payload technology are as follows:

- The technology currently available in conventional Western communications satellites is advanced compared to that of the Soviet Union and, in some cases, is 10 years ahead of the Soviet technology.
- Future Soviet communications satellites and satellite communications payloads will need to use solid-state amplifiers, miniature microwave integrated circuits, and multiple beam phased array antennas to be competitive or to fulfill some missions. The Soviet Union does not currently possess strong technologies in these areas. Thus, the Soviet Union is expected to attempt to acquire these technologies from the West or Japan.
- For dramatic improvements in a reasonable time, the Soviet Union must acquire components and manufacturing facilities and skills from outside its borders.
- With the advent of the Soviet SL-17 heavy launch vehicle, the Soviet Union is exploring placement of large (up to 30-meter) antennas on board its spacecraft. Larger diameter antennas do not, however, guarantee higher gain, since there is a limit to antenna gain posed by the surface

tolerance of the antenna. Such an antenna would likely operate at frequencies of less than 2 gigahertz (GHz).

- Potential military applications of a narrow beam antenna of up to 30 meters could have a significant effect on Soviet military satellite communications. Additionally, deployment of a high-powered satellite transponder in conjunction with a wide-beamwidth antenna (such as an Earth coverage horn) could have a significant impact on both the military and the commercial sectors by the development of a capable mobile satellite system.
- Soviet scientists and engineers are well versed in spread spectrum technologies, and they will likely use frequency hopped waveforms over satellites to satisfy strategic military missions.
- Advanced payloads such as those now flying in the INTELSAT-VI, on Italy's ITALSAT (launched to orbit in mid-January 1991), to be flown on NASA's ACTS (advanced communications technology satellite), and that proposed by Motorola for the low-Earth-orbit (Iridium) are well beyond the currently available technology of the Soviet Union.
- The Soviet Union could easily transmit 128 Mbps space-to-ground using its existing technology.

D. POWER GENERATION ON SPACECRAFT

Power generation on spacecraft can be accomplished by means of solar generators or by nuclear generators. The Soviet Union uses both types of generators. Solar generators are employed on all communications satellites, and nuclear generators are used for certain remote sensing satellites.

Solar power generators on Soviet communications satellites have power levels of 0.6 to 3.0 kilowatts (kW). The Soviet space station Mir provides 11 kW of primary power. Currently available power levels of nuclear generators are at the 10-kW level. Primary power can be increased to arbitrarily high levels through parallel connection power supplies. Weight and size are the only limi-

tations on an increase in spacecraft power on future missions. Considering the Soviet launch capability, the provision of up to 100 kW of power in low-Earth orbit would be practical, if such levels were needed.

The primary power needed for transmission of 128 Mbps is in the range of 40 to 200 watts, depending on the link configuration (this is a typical example; wide variations of power and bandwidth efficiency can be encountered, depending on the particular transmission system that is employed). However, it is clear that the current Soviet capabilities in the area of power generation are fully adequate for transmission of digital data rates of 128 Mbps and above.

For the coming years, Soviet objectives include:

- increasing the reliability of all spacecraft subsystems, including power generators;
- converting from government-funded programs to commercial programs; and
- teaming the Soviet spacecraft organization with Western aerospace companies to learn high-reliability techniques and to obtain assistance in commercial contracting.

E. EARTH TERMINAL RESEARCH

The Soviet Union does not appear to be placing much emphasis on improved Earth terminal technology beyond routine antenna performance enhancements and research into better production techniques for components such as low noise amplifiers and traveling wave tubes. Instead, Soviet researchers are placing greater effort on improved coding and modulation techniques and perhaps on exploiting the heavy launch capability provided by the new SL-17 launch vehicle to permit much larger (30-meter) satellite antennas in orbit. These larger satellite antennas could have a significant impact on Soviet Earth terminal requirements, as well as potential military use as pointed out below.

Specific findings related to Soviet Earth terminal research include the following:

- There are no Earth terminal (considered to be the radio frequency systems and equipment) limitations to transmitting or receiving a signal of 128 Mbps at frequencies up to 14 GHz. However, the Soviet Union appears to be logic rate limited to 40 MHz.
- The Soviet Union is placing increased emphasis on geostationary Earth orbits. Reasons for using geostationary Earth orbits are the reduced need for the sophisticated satellite tracking and hand-over schemes now needed for low-Earth and Molniya orbits.
- Aside from several new antenna configurations for the Ekran receive stations (television direct broadcast), the Soviet Union seems to be placing little emphasis on improving its Earth terminal radio frequency technology. Instead, it has apparently decided to focus efforts on increasingly sophisticated signal processing and coding to realize improved signal quality and reduced error rates in satellite links.
- Early in 1991, the Soviets began demonstrating a small R&D phased array C-band terminal to prospective Western clients. With this single exception, there appears to be little phased array Earth terminal research underway in the Soviet Union. No work on multi-frequency, broadband phased array antennas was uncovered.

The Soviet Union can be expected to continue to develop baseband processing capabilities to better use current technology and existing equipment. It can also be expected to continue minor improvement efforts on Earth terminal radio frequency equipment, especially in the areas of production and/or design automation. Neither of these areas has any particular military or political effect, but both have the ability to reduce the economic resources dedicated to communications in the Soviet Union and allied nations.

The largest impact on Soviet satellite Earth terminal technology will occur when and if the Soviet Union employs a relatively large spaceborne antenna.

Milestones to look for include testing of large-diameter parabolic dishes for space-based platforms and continued testing or deployment of the SL-17 heavy launch vehicle or a smaller version of the SL-17.

F. ANALOG-TO-DIGITAL CONVERSION, STORAGE, AND IMAGE PROCESSING

Communication data rates from spacecraft to the ground via a direct path or through a relay satellite can be limited by a number of factors. These include antenna sizes, noise levels, amplifier output power levels, modulation and coding schemes, propagation anomalies, interference transmission frequencies, and range. Of these factors, analog-to-digital conversion rates, onboard storage, and onboard processing can combine to limit the data rate transmitted from a spacecraft; conclusions in these areas are:

- Soviet high-resolution, high-speed analog-to-digital converters employ 8-bit pulse code modulation coders with clock rates of 40 megasamples per second or less.
- Soviet onboard satellite storage is limited, in terms of digital solid-state capacity and recorder bandwidth, to a few megahertz.
- Soviet digital logic rates appear to be limited to approximately 40-MHz rates.

These onboard limitations can combine to determine data rate transmission limits for space platforms. The Soviet Union will likely attempt to remove these deficiencies by acquiring high-speed logic capability, larger capacity onboard recording capability to 1 gigabit with high-speed playback (for example, 100 to 200 Mbps), and higher speed analog-to-digital converters.

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CHAPTER II BACKGROUND

This chapter presents background information on current and future Soviet space missions that could require high data rate transmissions.¹ These missions can require communications that are ground to ground via a relay satellite, low-Earth orbit to ground via a relay satellite, or direct to ground from a satellite in orbit about the Earth (see Figure II.1). This chapter highlights Soviet satellite communications, since these satellites dominate the Soviet literature on space communications. Soviet launch capabilities are reviewed and the possibility of new launch vehicles is discussed.

Figure II.1
Mission Configurations

¹ High data rate transmissions are defined here as a bit rate greater than 1 Mbps.

A. OVERVIEW OF SOVIET SPACE MISSIONS

Figure II.2 provides some information relevant to the role of communications in the Soviet space program. As shown, more than 80 Soviet communications satellites are operational. More than half of these are exclusively for Soviet military, intelligence, and diplomatic use, but there are several types of civil communications satellites discussed in greater depth in Section II.B below. Table II.1 presents major Soviet satellite constellations as of the end of 1989.

In addition to communications satellites, other classes of satellites have communications needs, the most stressing likely to be those associated with satellites with a real-time remote sensing capability. Of particular interest is the Soviet Astron program, an astronomical observation space mission. Astron 2 is now called "Granat" and has been accomplished with participation by the French.

Radioastron is a Soviet multi-satellite program scheduled to be launched during the 1990s, and beyond the year 2000. Up to six satellites are envisioned for the Radioastron program. Radioastron (cm) will consist of two satellites (1993-1996) launched into 77,000-km apogee elliptical orbits. These satellites will carry 10-meter-diameter radio telescope parabolic antennas for observations in the centimeter bands. Radioastron (mm) is a single satellite, scheduled for a 1996 launch, which will carry two 10-m parabolic antennas for millimeter-wave observations. This satellite is to be placed in a 77,000-km elliptical orbit as well. Radioastron (K-K/space-to-space) is a three-satellite system that will supposedly carry 30-m parabolic antennas, be placed in very high-Earth orbit, and monitor centimeter and millimeter wavelength. The Radioastron series will use the Spektrum satellite bus.

The Soviet Spektrum platform supersedes the Venera-based Astron/Granat vehicles, and the Soviets state that real-time data rates of 128 Mbps from high-Earth orbit (77,000 km) to the Earth will be required for the Radioastron mission. No relay satellite is envisioned for this mission except for the Radioastron (K-K) mission, which could require high-Earth orbit satellite crosslinks. The data rates for these possible crosslinks are not known at this time.

Due to the short mission times of most photographic reconnaissance and man-related spacecraft, the launch rates are not reflected in the Soviet resident population.

Figure II.2
Soviet Satellite Launches and Operational Satellites, 1990²

² N. L. Johnson, *The Soviet Year in Space 1990*, Colorado Springs, Colorado: Teledyne Brown Engineering, February 1991, p. 4.

Table II.1
MAJOR SOVIET SATELLITE CONSTELLATIONS

Program	Altitude (km)	Incl. (deg)	Period (min)	Normal Phasing	Primary Members as of 31 December 1989
Low-altitude communications	790-810	74	101	3 planes spaced 120°; 1 satellite per plane	Kosmos 1937, 1954, 1992
	1350-1550	74	115	~ 24 satellites in 1 plane	Kosmos 1852-1859, 1924-1931, 2008-2015
	1385-1415	83	114	2 planes spaced 90°; 6 satellites per plane	Kosmos 1994-1999, 2038-2043
	400-40,000	63	718	8 planes spaced 45°; 1 satellite per plane	Molniyas 1-68; 1-70 through 1-76
Molniya-1	400-40,000	63	718	4 planes spaced 90°; 1 satellite per plane	Molniyas 3-28, 3-32, 3-35, 3-36
Molniya-3	400-40,000	63	718	4 planes spaced 90°; 1 satellite per plane	Molniyas 3-27, 3-30, 3-33, 3-34
Geosynchronous	35,785	0-2	1436	19 locations above the equator	Raduga-22 (35°E), Gorizont-12 (40°E), Raduga-25 (45°E), Raduga-24 (49°E), Gorizont-17 (53°E), Raduga-17 (70°E), Gorizont-16/C1888 (80°E), Raduga-20 (85°E), Gorizont-13 (90°E), C1897 (95°E), Gorizont-19 (96.5°E), Ekran-19 (99°E), Gorizont-14 (103°E), Raduga-21 (128°E), Gorizont-18 (140°E), Gorizont-10/Raduga-18 (190°E), Raduga-23/C1894 (335°E), Gorizont-15/C1961 (346°E), Gorizont-11 (349°E)

Table II.1
MAJOR SOVIET SATELLITE CONSTELLATIONS (cont'd.)

Program	Altitude (km)	Incl. (deg)	Period (min)	Normal Phasing	Primary Members as of 31 December 1989
Meteor-2	940-960	83	104	3 planes spaced 60°; 1 satellite per plane	Meteor 2-16, 2-17, 2-18
Meteor-3	1230-1250	83	110	Deployment in progress (3 planes spaced 120°)	Meteor 3-2, 3-3
Early-warning	400-40,000	63	718	9 planes spaced 40°; 1 satellite per plane	Kosmos 1793, 1849, 1903, 1922, 1966, 1974, 1977, 2001, 2050
Ocean surveillance	250-270	65	90	1 plane; 1-2 satellites	None
	405-420	65	93	2 planes spaced 172°; 1-3 satellites per plane	Kosmos 1949, 2033, 2046, 2051
Okean world-wide Elint	635-665	83	98	Deployment in progress	Okean-1
	635-665	83	98	6 planes spaced 60°; 1 satellite per plane	Kosmos 1812, 1842, 1908, 1933, 1975
	850-855	71	102	Deployment in progress (4 planes spaced 45°)	Kosmos 1943, 1980

Table II.1
MAJOR SOVIET SATELLITE CONSTELLATIONS (cont'd.)

Program	Altitude (km)	Incl. (deg)	Period (min)	Normal Phasing	Primary Members as of 31 December 1989
Navigation	965-1020	83	105	6 planes spaced 30°; 1 satellite per plane	Kosmos 1904, 1959, 2004, 2026, 2034
	965-1020	83	105	4 planes spaced 45°; 1 satellite per plane	Kosmos 1655, 1816, 1861, Nadezhda 1
	19,000-19,200	65	676	Deployment in progress; 3 planes spaced 120°; 3 or more satellites per plane	Kosmos 1946-1948, 1970, 1972, 1987-1988, 2022, 2023

Source: N. L. Johnson, *The Soviet Year in Space 1989*, Colorado Springs, Colorado: Teledyne Brown Engineering, February 1990, p. 129

The Spektrum space vehicle is to be equipped with a 90-cm parabolic antenna for the transmission of real-time data to a ground station at 16 to 65 kbps or 18 to 128 Mbps. The 65-kbps rate is comparable to the early Granat transmission rates for information stored on board in a 150-megabit memory provided by the French. The 90-cm parabolic antenna is a key element in the determination of data rate capability for the missions shown in Figure II.1, since it is believed that the 90-cm parabolic antenna is a standard antenna and this size antenna, coupled with Soviet power-limited traveling wave tube amplifiers (20 W) and the use of K_u-band frequencies (14 GHz), serves to set the limits on Soviet space communications links.

In addition to Radioastron, there are a number of other future missions or continuations of current Soviet space missions that could require high data rate support. These include Mir, the Soviet space station; support for Buran, the Soviet space shuttle; follow-on programs for current electronic ocean reconnaissance satellites (EORSATs) and radar ocean reconnaissance satellite (RORSATs); Almaz, Okean-O, the Geostationary Orbit Meteorological Satellite (GOMS), and Lomonosov.

Under the Resurs-O program, the Soviet Union has a continuing Earth observation program that uses a Meteor space bus to carry a variety of sensors into low-Earth orbit. These sensors include multi-spectral scanners that result in 7.68-Mbps data rates, a microwave radiometer (80 kbps), and a side-looking radar (SLR) requiring 15-Mbps rates for unprocessed SLR imaging to 200 kbps for on-board processed SLR imagery. This would seem to indicate that Soviet researchers have developed onboard processing capabilities that allow a 75:1 compression ratio for SLR data. However, no information concerning the degradation incurred through this high-compression process is available. In Chapter VII, an attempt is made to determine the limitations on mission data rates imposed by onboard image processing constraints.

Soviet relay satellites and relay payloads are of high interest, since they can be used to support low-Earth-orbit missions such as Mir, Buran, and other missions requiring real-time flow of information over significant portions of a mission orbital period. The Soviet literature suggests that the first Soviet attempt to provide a relay capability was the Luch payload on geostationary satellites, Gori-

zont-5 in 1982 and Kosmos-1700 in 1985. More recently, Kosmos-1897 carried a relay capability to support the first Buran mission. Kosmos-1897 and Kosmos-2054 are considered an initial phase of the Satellite Data Relay Network (SDRN) for which the Soviet Union filed in 1981. The SDRN is similar in concept to NASA's Tracking and Data Relay Satellite System (TDRSS). SDRN is considered to be operational, but marginal in terms of performance. SDRN employs frequencies from 12.8 to 13.52 GHz for downlinks and 14.62 to 15.05 GHz for uplinks.

B. CURRENT SOVIET COMMUNICATIONS SATELLITES

The Molniya satellites refer to communications satellites in a 12-hour elliptical orbit. The Statsionar satellite network refers to the system of geostationary orbit satellites that provides fixed service satellite communications for the Soviet Union and many of its current and former allies. Statsionar satellites operate at various frequency locations in the 4/6-GHz, 8/7-GHz, 14-GHz (11-12), 6-GHz (702-726) MHz, 6-GHz (742-766) MHz, and 1.6/1.5-GHz bands. Several different types of spacecraft comprise the system, such as Ekran, Raduga, and Gorizont. Other satellites called Luch and Volna are involved in the development of new services at the 14/11-GHz and 1.6/1.5-GHz bands, respectively. Use of these bands is now being introduced operationally on the new Gorizonts. Mayak satellites are being introduced to expand Soviet maritime mobile service at 1.6/1.5 GHz. The capabilities of various Statsionar satellite transponders are discussed below.

A few characteristics of Soviet communications satellites are shown in Table II.2. The Molniya series of satellites date back to 1965, and the geostationary satellites started 10 years later. All the satellites are three-axis stabilized, as are many in the West. The power, mass, and equivalent-isotropic-radiated-power (EIRP) are comparable to Western satellites. The design lifetimes and number of transponders are significantly less than for communications satellites built in the West.

The Soviet satellites Molniya, Ekran, and Gorizont are shown in Figure II.3. Their general characteristics are similar to Western communications satellites, with the solar arrays and antenna reflectors, feeds, and horns. However, there are some significant differences: all the satellites have both deployable solar

arrays and body-mounted cells and the antenna reflectors have center feeds, rather than the off-axis feed antennas found in the West; this indicates smaller feeds and simpler beam patterns.

<p style="text-align: center;">Table II.2 CURRENT SOVIET NON-MILITARY COMMUNICATIONS SATELLITES</p>				
Orbit	Molniya-3	Ekran	Raduga	Gorizont
	Molniya (12-hour)	Statsionar (Geostationary)	Statsionar (Geostationary)	Statsionar (Geostationary)
First launch success	23 Apr 65	26 Oct 76	22 Dec 75	5 Jul 79
Stabilization	Three-axis	Three-axis	Three-axis	Three-axis
Power, watts	700	1,500	700	1,300
Mass, kg	1,500	2,000	1,250	1,000
Design lifetime (years)	3	3	5	5
Transponders	3	1	10	8
EIRP, dBW	32	52	29	28-46

Source: *The 1990 World Satellite Directory*

The Ekran system, a TV direct broadcast satellite, operates in the frequency bands from 702 to 726 MHz and from 742 to 766 MHz. The Ekran satellite transponders incorporate a power amplifier that delivers 200 W to the transmit antenna and, since the beam of the Ekran covers all of the Soviet Union, which would require a beam gain of about 30 dB, the EIRP of Ekran is 52 dBW (decibels above 1 W) at its beam center. It provides service to the entire Soviet land mass, especially to Siberia. Values of 52 dBW occur at latitudes of 60° to 70° N, and 34 dBW is available as far south as 50° N latitude. A principal advantage of the use of this band is the capability to construct relatively simple array antennas using dipoles or spiral elements to achieve gains ranging from 21 to 26 dB.

MOLNIYA 1

MOLNIYA 3

GORIZONT

METEOR-PRIRODA

METEOR 2

**KOBMOS
(OCEANOGRAPHIC)**

EKRAN

**KOBMOS
(NAVIGATION)**

Source: N. L. Johnson, *Soviet Year in Space 1987*, Colorado Springs, Colorado: Teledyne Brown Engineering, January 1988, p. 121.

Figure II.3
Representative Soviet Satellites

Raduga satellites carry five 36-MHz bandwidth transponders operating at downlink frequencies separated by 50 MHz between 3.4 and 3.65 GHz. These transponders deliver a power output of 4 W to an antenna with a gain of 24 dB ($9^\circ \times 18^\circ$ hemisphere beam) to yield an EIRP of 29 dBW. The uplinks are in the 5.725- to 6.225-GHz band and have a gain-to-noise temperature³ (G/T) of -17 dB/K. Raduga satellites also operate in the 8/7-GHz band.

Gorizont satellites are capable and powerful communications satellites. Gorizont has transponders with power outputs of 4, 15, and 40 W. They operate at the 6/4-GHz, 14/11-GHz, and 1.6/1.5-GHz bands. At 4/6 GHz, these transponders have the following capabilities:

- EIRPs of 29.5 and 35.5 dBW (uplink G/T values of -17 and -15 dB/K, respectively) in its $17^\circ \times 17^\circ$ global beam;
- EIRP of 29.5 dBW (uplink G/T of -17 dB/K) in its $9^\circ \times 18^\circ$ hemisphere beam;
- EIRP of 33 dBW (uplink G/T of -11 dB/K) in its $6^\circ \times 12^\circ$ area beam; and
- EIRP of 48 dBW (G/T of -17 dB/K) in a steerable $5^\circ \times 5^\circ$ beam.

At 14/11 GHz, the transponder delivers an EIRP of 38.5 dBW (G/T of -6 dB/K) in a $5^\circ \times 5^\circ$ global beam, and, at 1.6/1.5 GHz (for maritime mobile service), it delivers 28 dBW (G/T of -15 dB/K) in a $17^\circ \times 17^\circ$ global beam.

Molniya is a TV broadcast satellite that orbits the Earth in an inclined orbit of 62.8° with an apogee of 40,813 km, a perigee of a few hundred kilometers, and a period of 736 minutes (half a siderial day). This special orbit permits it to "hang" overhead at high northern latitudes for approximately six hours. Four Molniya satellites are used to achieve 24-hour service. Molniya has two apogees per siderial day, one over the Soviet Union and the other over Hudson Bay, Canada.

³ G/T is the spacecraft antenna gain divided by the spacecraft receiver noise temperature expressed in dB/°K, and is a measure of the satellite's receiving capability in terms of signal and noise levels.

Molniya carries three 36-MHz bandwidth, 30-W transponders operating on carriers separated by 50 MHz in the 6/4-GHz band, delivering an EIRP of 32 dBW to a global beam antenna. The antennas must be repointed about every 15 minutes except during one hour at the apogee. Its signal is received using 4-m diameter parabolic antenna-equipped Earth terminals.

C. SOVIET LAUNCH CAPABILITY

Launch capabilities in no way limit Soviet satellite communications. Soviet boosters had reached Earth orbit or beyond nearly 2,200 times by the end of 1989, which is more than two-thirds of all Earth's space missions. The Soviet Union currently operates a variety of launch systems (see Figure II.4). These range from the Kosmos that lifts 1,350 kilograms to low-Earth orbit, to the Energiya with a capability of 105,000 kilograms to low orbit, or 19,000 kilograms to geostationary orbit. As is done with many launch vehicles, the Soviet Union can put almost any desired communications payload into any desired orbit by varying the configuration, especially the number of boosters attached to the main launch vehicle.

Most communications satellites have been launched with the Proton from the Baykonur Cosmodrome at Tyuratam. This launch system can place about 2,500 kilograms into geostationary orbit, and a larger mass into a Molniya orbit. For a given mass, the Soviet communications satellites have much less communications capability than a Western satellite. Nevertheless, they have demonstrated that a number of transponders can be operational on such a satellite, and thus the launch capability is not a constraining limitation on communications rates.

The future of Energiya is uncertain. Its utility and cost effectiveness are being debated by Soviet space authorities. Furthermore, the Buran shuttle is delayed, and its future is likewise in debate. It is interesting to note that Energiyas are being marketed to the West for \$25 million, which is half the price of the US Delta II launch vehicle and almost one-eighth the price of current US heavy lift vehicles. This could be a Soviet attempt to sell their launch capabilities at a very low cost in order to achieve market penetration.

The Soviet Union currently operates 10 launch systems, although the SL-17 can lift conventional payloads or the Buran space shuttle. Payload capacities cited above are based on Soviet technical data or demonstrations and reflect operational launch constraints now in practice.

Source: N. L. Johnson, *Soviet Year in Space 1989*, Colorado Springs, Colorado: Teledyne Brown Engineering, February 1990, p. 12

Figure II.4
Soviet Launch Systems

Recent Soviet publications and interviews reveal a disenchantment with Energiya; however, there appears to be an attempt to develop a smaller version of Energiya based upon existing technologies, for example, a vehicle that uses the SL-16 Zenit rocket engines to bridge the gap between Energiya and Zenit.

This chapter has summarized the major factors that drive the research contained in this report, that is, can the Soviet Union support certain high data missions that have been proposed, and where is it headed with respect to satellite communications in the future? The following chapters report on the Soviet literature and interviews with Soviet scientists concerning the Soviet ability to support these missions and successfully carry out future satellite communications activities. In order to assess these abilities, the following technologies have been examined to evaluate their impact on space communications: satellite stabilization and spacecraft environments, communications payload technologies for commercial and military applications, spacecraft power generation, ground station technologies, and non-communications onboard processing technologies.

CHAPTER III

SATELLITE STABILIZATION AND ENVIRONMENT ON SPACECRAFT

A. SUMMARY

To assess any limitations in Soviet satellite communications, selected satellite technologies are examined. These technologies include spacecraft stabilization, thermal engineering, and other spacecraft environmental technologies.

- The spacecraft stabilization of Ekran, a three-axis system with gyroscopes, appears typical. There is an impressive number of Soviet papers on gyroscopes, but there is little information on other sensors and associated spacecraft control. Soviet stabilization control systems are considered to be years behind the West.
- In the use of satellite orbits and small stationkeeping thrusters, the Soviet Union is on a par with the West. Soviet researchers show a good understanding of the geostationary orbit, comparable to researchers in the West. They are the authority on the Molniya orbit, a 12-hour elliptical orbit. No information was found on small stationkeeping thrusters, but some references to electric-chemical propulsion indicate that the Soviet Union is pursuing lines similar to work in the West.
- In spacecraft thermal control, the Soviet Union is lagging behind the West, as no information was identified on the Soviet use of computer models of thermal nodes, and only a few Soviet references on radiative exchange could be located.
- Ground environmental testing of Soviet satellites, especially communications satellites, is lagging behind testing in the West, with no sophisticated computer-controlled shakers, and little evidence of modern thermal-vacuum tests.
- Soviet researchers have conducted some excellent research work on particle radiation at geostationary orbit.

In summary, while the Soviet Union lags behind the West in a few technological areas, none of these is a fundamental limit to Soviet satellite communications capability.

B. INTRODUCTION

Satellite communications can be limited by the technology used in building and testing satellites. This chapter discusses the spacecraft technologies required to build satellites (with the exception of the communications subsystem and the power subsystem which are discussed in Chapters IV and V) and covers a variety of methods and disciplines. The published Soviet satellite technology literature is sparse, and conclusions are often tentative. Since the Soviet Union has successfully deployed many satellites, it has found solutions to most critical problems. The limited amount of Soviet technical literature is therefore likely due to the lack of innovation. It should be noted that many state-of-the-art techniques in the West are not yet documented in the published literature.

The following general observations apply to all the fields of Soviet spacecraft technology in this chapter:

- **Independent evolution.** Soviet researchers appear not to have had detailed exposure to Western spacecraft technology, and their solutions may have evolved from different methods, which may be equally valid.
- **More massive subsystems.** In the West, "better" often means a smaller mass. The Soviets have in some areas used simpler, more massive solutions, which are otherwise equally effective. Their heavy booster capability makes such solutions practical.
- **Limited access to computers.** In areas where Western researchers have made extensive use of computers, Soviet workers have often found other methods.
- **Impressive progress in a few selected areas.** Soviet researchers have the skills to advance to a level beyond those in the West, but this has happened only in a few areas where they have chosen to do so. Notable

examples are gravity gradient stabilization of spacecraft and use of star trackers.

C. DISCUSSION

The following sections address three major topics: spacecraft stabilization, stationkeeping in geostationary orbit, and spacecraft environment (which includes thermal control, spacecraft testing, reliability, and particle radiation in space).

1. Spacecraft Stabilization

Modern satellites that feature high data rate communication often use beams that concentrate the energy on the Earth or directed at relay satellites. Since the pointing of these beams must be controlled, it is necessary to control the orientation of a satellite. This can be accomplished successfully in several different ways. The Soviet methods have evolved differently than those of the West. In the United States, two major methods have been used, as well as a host of variations. It is not possible to make a simple statement as to which method is better, or which system is more advanced.

a. Stabilization Configurations

Some satellites are spinners, with part of the spacecraft spinning and the other part despun. Early US satellites such as Telstar, Relay, and Early Bird were spinners. A major improvement in spinning around the minimum moment of inertia was pioneered by Hughes Aerospace with TACSAT (tactical satellite) and INTELSAT-IV, and new levels of sophistication are being reached in INTELSAT-VI. Concepts being developed in the West include energy sink theory, passive nutation damping, active nutation damping, automatic spin axis control, and super spin in transfer orbit. The Soviet published literature indicates that the Soviet Union is lagging behind the United States in these areas by one or two decades. The only Soviet reference to such work is an article that describes a simple method of nutation damping using a flywheel (Pivovarov, 1987). However, satellites can be built without using the spinner concept, and Soviet researchers may not consider this expertise to be essential.

Modern geosynchronous communications satellites are three-axis stabilized, with one axis always pointed at the Earth, and a second axis pointed more or less at the North Pole. Usually, there are solar panels that rotate around the north-south axis. Typical communications satellites use a biased momentum wheel for ease of control. All the Soviet communications satellites in geostationary orbit are three-axis stabilized, including Gorizont, Raduga, and Ekran (Kalinovich, 1988).

Gravity gradient is a method used in spacecraft stabilization, and is based on a principle that a long dumbbell tends to line up along the vertical axis. Gravity gradient is not suitable for modern communications satellites with precision pointing requirements, and the effect is much weaker at geostationary orbit than in low-Earth orbits. This method is cited here because of the impressive quality and quantity of Soviet documents on gravity gradient techniques (for example, Pomanenko, 1988). This indicates that, if other methods of spacecraft stabilization had been developed to a similar degree by the Soviets, literature would be available. Gravity gradient stabilization techniques are not expected to be used on future Soviet satellite missions that require precision pointing and high-data-rate transmissions.

b. Sensors for Attitude Control

Many Western satellites use Earth sensors and Sun sensors for the primary detection of attitude errors. The use of radio frequency sensors has increased in the West, especially as narrow antenna beams have increased the required accuracy. The Soviet Union, on the other hand, appears to place more reliance on star trackers and gyroscopes. No Soviet references to Earth sensors and Sun sensors were identified. This does not mean that these sensors are not built and used, but their design and use has not prompted many technical papers.

Star trackers have not been used frequently in communications satellites in the West, primarily because they are heavier than Earth sensors, and significantly heavier than Sun sensors. Many designers of communications satellites have gone to considerable trouble to avoid the need of a yaw sensor by relying on Sun sensors when they can be used, and relying on angular momentum when

the Sun is not available. Soviet researchers place less emphasis on mass reduction and more emphasis on the use of star trackers (Ivashkin and Zadykhina, 1988).

The use of gyroscopes was discouraged for early US communications satellites because of life-expectancy problems, with questions as to whether the mechanical bearings could be used continuously for the many years of design life. Gyroscopes are now available in the West that fulfill life-expectancy requirements with confidence. The Soviet Union makes extensive use of gyroscopes, and the literature (such as *Soviet Weekly*, 1989) on the subject is abundant. Pelpor and coworkers (1986, 1988) have written two volumes that indicate a thorough knowledge of gyroscopes. While there are differences in detail, Soviet gyroscope capabilities appear to be on a par with those of the West. Soviet state of the art in gyroscopes or star trackers poses no limitation on high data space missions today, or in the immediate future.

c. Control Methods

A control system is needed to manage a three-axis system, using the input from several sensors, and controlling wheels, motors, and/or thrusters. For the Soviet space shuttle Buran, the control and navigation is managed with a three-ton system which includes 1,100 electromechanical instruments. Even without the use of sophisticated microprocessors, it is difficult to understand why three tons of mass are required for this function.

On the mathematical side, Soviet researchers are sophisticated. Kavinov (1988) mentions the use of quaternions. Akulenko (1988) has performed notable work on finding the minimum number of pulses (generally two) to reach a desired stabilized spacecraft attitude. On the other hand, the Soviet Union appears to be years behind the West in actual implementations, especially in the use of onboard computers and in reducing the mass of the control system. However, with its heavy launch capability, the Soviet Union can launch satellites with bulky control systems that can satisfy high-data-rate communications missions.

2. Stationkeeping in Geostationary Orbit

a. Use of Orbits

Historically, many Soviet communications satellites were in Molniya orbits, a 12-hour inclined orbit with the apogee at the extreme northern latitudes. Since these satellites spend most of their time in the northern hemisphere, they are especially useful for northern latitudes. In the use of Molniya orbits, the Soviet Union is well ahead of the West. However, these orbits require tracking by the Earth station antennas.

The Soviet Union has used the geostationary orbit with Statsionar, Gorizont, and Raduga satellites (Zubarev, 1989). This discussion will be limited to this orbit. The geostationary orbit is a unique orbit, with unusual properties, unusual stationkeeping requirements, and an unusual number of satellites (especially communications satellites). Soviet researchers have an excellent understanding of this orbit. Kantor et al. (1988) provide detailed discussions on the geostationary orbit as a limited resource, and show a grasp of both its potential and limitations. Reshetnev et al. (1988) discuss the perturbations a satellite experiences in geostationary orbit, including the geopotential perturbations that produce a longitudinal acceleration, the lunar and solar perturbations that produce a north-south oscillation (inclination of the orbit plane), and the solar radiation pressure that produces an east-west oscillation.

On the mathematical side, Soviet researchers have a thorough understanding of satellite orbits, and there is much evidence of Soviet orbital mathematical capabilities. Sukhanov (1989) describes a universal set of orbit programs. A reference to Hill's equations by Bolotin (1988) shows that these techniques, first used by Hill on the Moon's orbit, are being applied to present Soviet orbital problems. These equations are particularly applicable to both a satellite rendezvous with another satellite, and to a satellite rendezvous with an assigned longitude on the geostationary orbit (in other words, stationkeeping).

b. Spacecraft Propulsion

Thrusters are necessary to keep a satellite in its proper location in geostationary orbit. Many Western satellites use a monopropellant system with hydrazine as a fuel. In a small number of satellites, the thrust is increased by adding some electrical energy to the available chemical energy. Some satellites now use a bipropellant system with separate tanks of fuel and oxidizer.

The Soviet Union probably uses one or more of the above systems, although no specific description of a stationkeeping thruster was found. Database searches on the keyword "hydrazine" resulted in a large number of Soviet references on other uses of the chemical, but no references on its use in any thrusters. Grishin and Leskov (1989) have reported on electric rocket motors. Other publications reviewed included a paper by Rylov (1988) on electric-chemical propulsion, and a paper by Zhurin et al. (1988) on electro-thermal and plasma thrusters. All these are similar or related thruster types. With respect to small thrusters, the Soviet Union is probably on a par with the West, but no Soviet literature with which to make an accurate evaluation was identified.

Personnel at the Applied Mechanics NPO (Scientific Production Association, Krasnoyarsk) have stated that the plant builds its own plasma thrusters for orbital control of the spacecraft. These 200-W/g electrical thrusters consume 1.6 kW of electrical power, they are space proven, and they presently have an operating life expectancy of 14,600 hours. When operated for four hours daily, these thrusters have a life expectancy of 10 years. The thrust developed by the 3.5-kg unit is "78.5 milli-Newton" (mN), which is considered adequate for fine tuning of the Molniya highly-elliptical orbits, as well as inclination control and position maneuvers of geostationary spacecraft.

3. Spacecraft Environment

The following sections cover other aspects of spacecraft technology, including thermal control, spacecraft testing, spacecraft reliability, and the particle radiation encountered at geostationary orbit. These are important factors in building any spacecraft.

a. Thermal Control

The majority of the work in spacecraft thermal design deals with predicting the temperature for a spacecraft in orbit for many points in the spacecraft. The remainder of the work deals with modifying the spacecraft to change the temperatures if they do not fall in an allowable range. Usually, temperatures can be predicted within an accuracy of $\pm 5^{\circ}\text{C}$. If thermal predictions are poorer, equipment can be built to allow wider temperature extremes.

Soviet researchers show evidence of understanding the fundamentals of spacecraft thermal design. Pankratov (1988) wrote a book entitled *Fundamentals of Thermal Design—Space Transport Systems*, which describes the effect of surface properties, the heat loads from the Sun and Earth, and conductivity and insulation. A book by Malozemov and Kudryavtseva (1988), *Optimization of Systems for the Thermoregulation of Spacecraft*, discusses techniques that are more appropriate for manned space stations than communications satellites because they include gas and liquid heat exchangers and foam and powder insulation.

Soviet researchers definitely understand the basics of computer thermal modeling, in which the spacecraft is divided into a number of isothermal nodes. Darin and Mazhukin (1988) discuss adaptive differencing grids, which are related to thermal modeling. However, there is little evidence to indicate that thermal modeling is used as extensively in the Soviet Union as it is in the West. Soviet researchers have the fundamental capabilities needed to design and build spacecraft, but they do not possess the predictive accuracy that is possible and necessary for long-life spacecraft.

b. Spacecraft Testing and Reliability

There are a variety of methods for testing spacecraft, but two tests are basic: vibration tests and thermal-vacuum tests. These are usually performed at both the subsystem level and on the integrated spacecraft. The vibration test provides final assurance that the spacecraft will survive the launch environment, and the thermal-vacuum test simulates the space environment. It would be difficult to build reliable spacecraft without these tests.

Vibration tests are described in several Soviet papers (Khayrullin et al., 1988; Yuryev 1985). These tests are described as mechanical shaker, electromagnetic shaker, or electrodynamic shaker, but they probably all refer to a device that produces vibration with an alternating magnetic field (similar to the coil in a loudspeaker). In the West, vibration tests have become quite sophisticated, calculating the vibration levels by matching launch vehicle and spacecraft structural computer models, lowering the excitation near a spacecraft resonance, and making extensive use of computers for driving both the shaker and for analyzing the test results. The Soviet papers reviewed were more concerned with the mechanical aspects of mounting the object to be tested. This indicates that the vibration tests are fairly simple and straightforward. This can still lead to reliable satellites, but they may be structurally overdesigned to survive an overtest.

No references to thermal vacuum tests were located in the Soviet literature. This does not mean that such tests are not being performed. It probably means a simple test system, without elaborate means to duplicate the temperature environment, is being used.

Other tests were described. Melnikov et al. (1984) measured the moment of inertia of a spacecraft with a straightforward rotational pendulum method. Kononov et al. (1985, 1987) described tests on a linear accelerometer and a pendulum accelerometer. Much of the spacecraft testing near a launch date is performed under a tight schedule, and technical papers are published in the West only (if at all) when a novel test technique is used.

c. Particle Radiation at Geostationary Orbit

A few Soviet papers on particle radiation at geostationary orbit were noted. Vakulin and coworkers have published papers on the distribution of particles during a quiet period, and on charge disturbances at geostationary orbit (Vakulin et al., 1988a-b). These are based on observations from satellites stationed at specific longitudes.

There are several effects of particle radiation on communications satellites: the particles produce permanent damage on solar cells; penetrating radiation can

damage internal electronic components; and charges can accumulate on surfaces and produce spark discharges, which can change the state of electronic registers.

D. PROJECTIONS FOR THE FUTURE

No Soviet surprises are likely to develop in the next five to 10 years. The Soviet Union undoubtedly will build and launch new satellites using fundamental spacecraft technology. The few areas where the literature indicates some determined effort demonstrate good results, but these do not have a major effect on the entire satellite. Two developments are important to Soviet progress in spacecraft technology:

- The widespread use of computers could have a significant effect on stabilization control, spacecraft testing, and thermal modeling and lead to longer spacecraft life expectancy through improved, more reliable designs.
- A more open and competitive environment could accelerate the changes in Soviet spacecraft technology. Competition should cause greater interest in lighter, more reliable designs.

Current Soviet stabilization, thermal engineering, stationkeeping, and other spacecraft environmental factors are not seen as major limitations on space missions requiring high-data-rate transmissions.

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CHAPTER IV

COMMUNICATIONS SATELLITE PAYLOAD TECHNOLOGY

A. SUMMARY

This chapter focuses on the communications payload technology used on board satellites for distribution of civil public switched telephone and television communications, and for military satellites. It represents a broad review of Soviet technical and scientific journals, Soviet texts, and numerous US and international publications devoted to satellite communications.

Conclusions drawn from this review include the following:

- The technology available in conventional Western communications satellite payloads flying today is advanced compared to that of the Soviet Union. The Soviet payload technology is like that of the late 1970s in the West.
- In order to be competitive with the West and Japan, Soviet communication satellites of the future will need solid-state amplifiers, miniature microwave integrated circuits, and multiple beam phased array antennas.
- To change in a reasonable time, the Soviet Union would need to buy components and manufacturing facilities and skills from outside its own borders.
- Advanced payloads such as those now flying in the INTELSAT-VI, on Italy's ITALSAT (launched to orbit in mid-January 1991), to be flown on NASA's ACTS (advanced communications technology satellite) and that proposed by Motorola for the low-Earth orbit Iridium are beyond the reach of the Soviet Union.

B. INTRODUCTION

Communication satellites can operate in geostationary orbits as radio signal repeaters located at altitudes so high that any one of them can simultaneously see over one-third of the surface of the Earth. At this high altitude (35,700 kilometers [km], or 22,300 statute miles), a satellite can see and hence connect among Earth terminals located anywhere in a field of view 16,000 km across. Many repeaters can be operated in parallel on board the satellite to provide tens of thousands of long-distance radio communications circuits. In the early 1960s, this unprecedented capability to interconnect widely separated Earth stations simply by pointing antennas at the satellite combined with the demonstration of economical launchers and spacecraft communications payload technology fueled the creation of the communications satellite industry. In comparison, contemporary terrestrial microwave technology uses radio repeaters located on towers several hundred feet high and transmitting to and receiving from other towers over distances of 50 to 150 km.

The Soviet Union has been using satellite communications since 1965, when it launched the Molniya communications satellite system, comprised of four satellites in the same orbit, canted at an angle of 62.8° relative to the equatorial plane, having high eccentricity (high apogee and low perigee) and a period of half a sidereal day. It carried television signals at 6/4 gigahertz (GHz). The four satellites were timed to rise to their apogees over the northern Soviet Union at intervals separated by a quarter of a day. This gave Soviet researchers non-stationary overhead satellite service at 62.8° North (N) latitude for 24 hours a day, each satellite being used for approximately 6 hours. The first four Molnias provided one television channel between Moscow and Vladivostok for 24 hours a day.

In the same year, on 5 April 1965, INTELSAT launched its INTELSAT-I "Earlybird" international communications satellite into a geostationary orbit at an altitude of 35,700 km above the Equator over the Atlantic. This one satellite provided full-time service for 240 telephone circuits or one television channel between North America and Europe. Thus, in the same year, communications via satellite started in the West and in the East.

In the ensuing years, the Soviet Union also adopted geostationary orbits like those of INTELSAT, in preference to the non-stationary Molniya orbits. Geostationary orbit satellites now dominate the Soviet Stationar system, the backbone of the Soviet national and Intersputnik satellite systems. Even so, the Molniya orbits are still used because they provide high-elevation-look angles to the satellite at high northern latitudes where geostationary satellite look angles are close to the horizon.

C. DIFFERENCES IN TECHNOLOGY—EAST AND WEST

Even though the satellites of East and West exhibit many similar operating characteristics, such as operating frequencies and equivalent satellite and Earth terminal radiated power (equivalent isotropic radiated power/EIRP), the East and the West have followed independent routes in the technology used on board the satellites. The principal reason for the similarities is the adherence to the International Telecommunications Union recommendations, observed by the nations of East and West alike, and the similar physical constraints of the systems. However, the implementation technologies differ in many respects. Twenty-five years since the beginning of satellite technology, the differences between Eastern and Western approaches are becoming very apparent. In brief, the Soviet Union has not been innovative in the application of new technology to onboard communications payloads.

A review of the Soviet technical literature, extending over the years from 1980 to 1989, shows an absence of most of the implementation technologies that are commonly used in the latest generations of modern Western designs. Notably lacking are the following technologies:

- lightweight carbon fiber composites in bus structures and in radio frequency (RF) components;
- solid-state power amplifiers;
- multi-element focal plane antenna feeds;
- multibeam antennas and frequency spectrum reuse;
- tightly packed transponder filters with minimum guard band;
- large numbers of transponders on a single satellite;

- high-density occupancy of the assigned spectrum space;
- onboard static and dynamic microwave switching to improve connectivity among multiple beams; and
- long on-orbit lifetime design (for example, 10 years today, 13 years in the near future for US satellites).

All of these technologies or features are highly developed in current Western designs, but do not seem to be exercised in the Soviet designs. By application of such technologies, the Western satellites are lighter, larger in communications capacity, more efficient, more flexible and longer-lived. No Western communications satellite construction company could expect to find a buyer for its communications satellite products if it did not practice these modern principles.

Study of the published Soviet literature reveals, from a communications capability point of view, that the Soviet satellite communications payloads currently in the geostationary and high-inclination angle, high-eccentricity Molniya orbits are on a par with those used in the international and national systems produced in the West. However, the implementation technology used on board is more like that available in the late 1970s, when discrete, solid-state, low-noise, and low-signal-level amplifier technology was used in the receivers and traveling wave tubes (TWTs) in the power amplifier stages. There is no evidence of the Soviet use of high-power, solid-state amplifiers, currently used exclusively at the 6/4-GHz bands in the West; nor of Soviet use of onboard digital processing technology, such as that already flying on board INTELSAT-VI and the baseband demodulator/modulator and digital switch matrix on Italy's ITALSAT; nor of the very advanced onboard baseband digital processing and switching technology currently being constructed by GE and Motorola for the NASA advanced communications technology satellite (ACTS).

On a theoretical and conceptual level (revealed by the intellectual strength apparent in the Soviet literature), there is a pent-up capability to understand and contribute to the future satellite communications technology. Soviet researchers appear to lack either the capability or desire to apply the concepts to the Soviet commercial satellite communications world.

The Soviet Union seems to be practicing technology that is circa 1975, and seems to be satisfied. One explanation for this is the existence in the West of a fiercely competitive communications satellite manufacturing industry involving US, European, and Japanese companies. By comparison, the Soviet Union is a closed, central-government-dominated society in which competition cannot flourish. Furthermore, the Soviet Union developed and mass-produced heavy lift launchers (principally for political and military reasons) as early as 20 years ago, and these vehicles can lift heavy satellites into geostationary orbit. Thus, the need to build lightweight, long-life communications satellites was not a pressing requirement for the Soviet Union.

Based on these observations, it is concluded that the Soviet Union is not in a position to construct satellite communications payloads of the caliber of those presently available in the West. If new enhanced capability satellite generations are to orbit over the Soviet Union, they will probably use communications payloads constructed in the West. Indication that such is the case appeared in an interview¹ with the editor of *Satellite News* during a recent international conference entitled "The Role of Satellites in Sound and Image Transmission" (sponsored by *Satel Conseil* in Paris), Intersputnik Director General Boris Chirkov described as a "Soviet initiative" a new Soviet satellite system, based largely on West German payload technology, using Soviet bus technology. The planned "Romantis" satellites would have to be approved by the Intersputnik Council. Whether or not Intersputnik will actually proceed with this idea is not known, but it does indicate recognition on the part of a high Soviet official of the superiority of Western technology.

Future satellite communication research and development exhibits the same trend. US, European, and Japanese research and development are moving toward satellite communications payload architectures that will use:

- multiple high-power satellite beams, some of which can dynamically hop to the locations of Earth terminals, to achieve far greater communications capacity into smaller Earth terminal antennas;

¹ *Satellite News*, 13, 39 (1 October 1990).

- miniature microwave integrated circuits;
- onboard microprocessors and VLSI and LSI digital components;
- onboard demodulation to recover the baseband digital signal and remodulation of the signals on the downbeam to achieve signal regeneration advantages;
- optimum transmission methods that are different on the up- and downbeams (such as low-rate frequency division multiple access [FDMA] or TDMA [time division multiple access]/FDMA carriers on upbeams and high-rate TDMA carriers on the downbeams);
- onboard forward error correction decoding and coding independently applied to uplinks and downlinks to overcome rain loss margins at Earth terminals;
- onboard rerouting and reconfiguration of baseband channels among multiple up- and downbeams in the same sense as done in telephone switching centers on Earth;
- demand assignment of the space segment channels among the Earth terminals to achieve a large channel concentration loading advantage;
- fast packet satellite onboard switching that simplifies the onboard routing of information through the satellites;
- digitally implemented onboard carrier demultiplexers and demodulators that will permit hundreds of FDMA and TDMA/FDMA carriers to be recovered on board the satellite.

These are but a few of the concepts that are being actively explored on experimental Western and Japanese satellites. The Soviet published literature does not reveal satellite onboard technologies to the level that Western and Japanese publications have detailed these technologies. This is not because Soviet researchers are unaware. There is evidence of Soviet understanding of what is possible.

However, there is little evidence that applications are being pursued in the Soviet Union with the vigor apparent in the West and Japan. If advanced on-board communications payload technologies are being applied, it must be in Soviet classified programs.

There is some innovation in Soviet satellite communications transmission technology. The Soviet TDMA-40 system uses 40-megabits-per-second (Mbps) burst rate TDMA to interconnect widely distributed Earth terminals using transponders with 34 megahertz (MHz) of bandwidth. The Soviet TDMA-60 system uses a combination of channel coding and octal phase-shift-keyed (OPSK) modulation to operate the TDMA at a burst rate of 60 Mbps in the same 34-MHz bandwidth transponders. This is the highest bit rate mentioned in the Soviet literature reviewed. This pales in comparison to INTELSAT's 120-Mbps TDMA system, which has been used extensively for international digital communications since 1985 on INTELSAT-V satellites, and is now being extended to satellite-switched TDMA on the new INTELSAT-VIs. This system operates at a bit rate of 120 Mbps in 72-MHz-bandwidth transponders. Further Western modulation developments have increased the bit rate achieved in the 72-MHz-bandwidth transponders to 140 Mbps, and more recently work is underway to increase this to 155 Mbps. Both of these use OPSK combined with error correction coding.

The remainder of this chapter deals with the technology of building the communications payloads. Specifically, the focus is on the technology of low-noise amplifiers for receivers, high-power amplifiers for transmitters, filters for selecting frequency bands, and antennas for reception and transmission that are needed for implementing conventional payloads as they exist in current Soviet practice, and compared to Western-Japanese practice. Also presented is a discussion of future advances expected from trends in new experimental Western satellites, and an attempt to identify where the future of Soviet technology may be headed.

D. SATELLITE/EARTH TRANSMISSION OF 120 OR 140/155 Mbps

In order to assess the ease with which the Soviets could increase their communications or remote sensing satellite transmissions to 120 Mbps or above, we will cite the example of INTELSAT-V.

To transmit 120 Mbps or 140/155 Mbps modulated carriers at 4 GHz from an INTELSAT-V in geostationary orbit to earth, the satellite transmits a power times antenna gain of 30 dBW (1,000 W) in the direction of the receiver (this is called the equivalent isotropic radiated power/EIRP), and the Earth antenna has a diameter of 15 meters and a gain-to-noise temperature (G/T) of 34 decibels (dB)/kelvin (K). If the satellite is at a low-Earth orbit altitude of only 200 miles, then the sum G/T + EIRP can be reduced by $20 \times \log(22300/200) = 40.9$ dB. Thus, one could reduce the satellite power by 100 times (20 dB) to 10 W, and the antenna diameter by 11 times (20.9 dB) to 1.4 m, and still receive the signal. Accomplishing the same transmission at K_u-band requires an increase of about 6 dB in the sum G/T + EIRP to overcome increased path loss margin. If the same diameter of Earth terminal is used at K_u-band as at C-band, the G/T of the Earth terminal is increased by 8.8 dB simply by going to the higher frequency. This more than offsets the needed increase in G/T + EIRP. Thus, transmission of 120-Mbps or 140/155-Mbps carriers from geostationary or from low-Earth orbit to Earth is a simple matter with today's Western communications satellite technology, and, for that matter, current Soviet technology also is sufficient to accomplish these links.

E. CONVENTIONAL SATELLITE COMMUNICATIONS TECHNOLOGY

The following is an overview of the state of Soviet technology in the conventional and advanced commercial satellite communications payload areas.

1. Conventional Transponder Technology

The Soviet Union is fully competent in the area of conventional "bent-pipe" (simple relay) communications payloads and has the capability to design and build its own payloads. This is evident from a description of the Soviet national satellite communications system given by Kantor and Timofeyev (1988), and provided in Appendix A to this report.

To have achieved current capabilities, the Soviet technology must include the full spectrum of skills needed to construct spaceworthy critical components of the conventional satellite communications payload, such as: solar arrays for

source power; batteries for operation in the dark; electronic power conditioners; low- and high-power TWTs and klystrons (both of which are vacuum-tube technology); microwave cavity filters (evidence of the use of lightweight carbon fiber composites was not found); solid-state mixers and frequency converters; solid-state, low-noise receivers; and conventional single-element linear and circular polarized reflector-type and horn receive and transmit antenna systems. All communications satellites currently being used in the Soviet Union are three-axis stabilized platforms rather than spinners.

2. Solid-State Device Technology

The Soviet capability to fabricate solid-state technology devices appears poor by Western standards. There is little evidence that solid-state power amplifiers are being used in any Soviet satellites. This is an area in which significant strides have been made in the West. However, the Soviet knowledge of solid-state physics and understanding of the advantages of gallium arsenide, high-electron mobility devices, and the use of field effect devices in RF applications is well advanced. Furthermore, because the US technical literature is far less restrictive in material regarding advanced technology, a good student can learn nearly everything s/he needs to know to understand and design devices. All that is needed are the materials and facilities to construct devices.

The principal reason for the narrow breadth of Soviet application of solid-state technology is lack of the facilities to make the basic materials and the means to fabricate devices that consistently work. However, it is a mistake to assume that Soviet researchers do not possess sufficient facilities to fabricate (on a limited scale) devices needed for intelligence and other military satellite applications. These applications are simply not mentioned in the technical journals.

Fabrication of solid-state devices using silicon and gallium arsenide requires a capability to make very pure substrates of the material, to lay down on the substrate the patterns of the devices to resolutions at the submicron level, and to deposit the layers of dopants and metals needed to construct the devices. The process requires high-resolution devices, such as electron beam lithography machines to impose the patterns, and vacuum deposition facilities to impose the layers. The Soviet Union is behind in the construction of these basic manufac-

turing facilities for both the submicron analog miniature microwave integrated circuit (MMIC) and digital large-scale integration/very large-scale integration (LSI/VLSI) devices. However, there is much evidence to suggest the Soviet Union will eventually obtain these capabilities. Lachashvili and Traube (1988), in the book *Design of Electron-Beam Devices*, indicate a level of understanding that could lead to independent developments in fabricating such submicron devices on a reasonably large scale.

3. Satellite Antenna Technology

Soviet satellite antenna technology does not appear to be on a par with that used in conventional communications satellites constructed in the West at the same bands of operation. The Gorizont has reflector antennas for its 4/6-GHz $5^\circ \times 5^\circ$ spot beam and for various 14/11-GHz coverages. The feeds for these reflector antennas are not as advanced as those used on the INTELSAT-V, -VI, and -VII. The INTELSAT antennas use more complicated offset feed systems, mainly to facilitate beam shaping and in-orbit adjustments needed to accommodate three ocean regions of operation. Soviet researchers use conventional horn antennas for the broader coverage beams. The UHF Ekran antenna uses a 6×16 array of spiral elements, a fairly conventional design for satellite communications payload operation at ultra-high frequencies. The Molniya satellite, which has wide area coverage, uses relatively simple horn antennas.

The Soviet Union has a reasonable theoretical capability to deal with the complexities of more complicated antenna designs. This is evidenced by the sophisticated array antenna design approaches and the application of optical processing concepts to radar as well as sonar signals, as described by Voskresenskiy et al. (1986).

4. Transponder Technology

One of the most important components for constructing communications satellite payloads is the power amplifier used in the final stage of the transponder. The power amplifier and the antenna gain (determined by the beamwidth) are the prime factors in determining the satellite equivalent-isotropic-radiated-power (EIRP). EIRP governs the transmission bandwidth and diameter of the

Earth terminal parabolic antennas needed to receive the signal. In general, the diameter of the Earth terminal's antenna must be large enough to yield an antenna gain-to-noise-temperature (G/T) ratio (which, in the Soviet Union, is referred to as the receive quality factor "Q") sufficient to achieve the margin needed for a specified bit error rate or baseband signal-to-noise ratio availability objective. The sum of satellite EIRP and Earth terminal G/T provides the driving component of the link budget equation.

Many Soviet papers deal with experimental investigation and theory of semiconductor devices; however, nothing was found on the subject of solid-state power amplifiers suitable for use as transponders on communications satellite payloads. It is unreasonable to believe the Soviet Union has no capability to fabricate such devices; rather, it is likely that Soviet researchers feel more secure with devices, such as traveling wave tubes, in which their state of the art is comparable to that of the West. It is also likely that Soviet work on semiconductor devices would be first applied in special scientific and military applications and this is not likely to be published in the scientific literature.

F. ADVANCED SATELLITE COMMUNICATIONS TECHNOLOGY

1. Miniature Microwave Integrated Circuits

An area conspicuous by its omission from the Soviet literature is miniature microwave integrated circuits (MMICs). Such circuits are extremely important to future communications payloads. They make it possible to fabricate microwave circuits in monolithic form on solid-state substrates to achieve the integration of miniature and integrated circuits. No mention of work in this area was found in any of the Soviet scientific journals reviewed, although there is mention of planar circuits, the technology needed to proceed to MMIC technology. It takes nearly five years to develop the skill base needed for the MMIC, and it does not seem to exist in the Soviet Union now. However, it is evident that the knowledge base to understand the theory and advantages of MMIC is not lacking. Design of miniature monolithic microwave circuits is a complicated art that requires considerable computer-aided design software. The Soviet Union has traditionally been weak in computer technology, especially in the development of the software needed to perform jobs like those required for MMIC. Further-

more, the equipment to fabricate devices such as E-beam lithography and vacuum deposition equipment and the skills to operate this equipment are not readily available in the Soviet Union. These are similar to the equipment and skills needed for LSI and VLSI digital circuits. Soviet researchers are concentrating on improving their skills in computer applications and computer-aided design, as evidenced by a special issue of *Radio Electronics and Communications Systems* (Vol. 11, No. 5, 1988) on computer-aided design. This area is critical to successful creation of an MMIC fabrication and design capability.

2. Digital Transmission Technologies

Soviet researchers frequently mention that they are using digital transmission technology exclusively for all of their satellite communications systems, with the single exception of TV, for which frequency modulation is being used. A good example of their use of digital transmission is their time division multiple-access (TDMA-40) system, which requires a transponder bandwidth of 34 MHz to carry the 40-Mbps quadrature phase shift keyed modulated carrier and a 60-Mbps version of the same system that uses the same bandwidth by use of a combination of coding integrated with octal phase shift key in about the same bandwidth and with the same energy per bit to noise spectral density ratio. This exclusive devotion to digital transmission techniques must not be construed as implying equal skill in the use of digital signal processing techniques for satellite communications payloads.

3. Advanced Onboard Processing

In the United States, Europe, and Japan, advanced design communications payloads are being explored that go far beyond those of the conventional bent-pipe transponder designs dominating the current generation of commercial satellites. Probably the most advanced of these is NASA's advanced communications technology satellite, currently being constructed by a team led by GE, with COMSAT and Motorola as subcontractors. The ACTS will demonstrate five new technologies to significantly improve the competitiveness of satellite communications in the face of a terrestrial telecommunications environment rapidly moving to high-capacity fiber light guides that provide low per-circuit cost on high-volume telephone trunks. ACTS intends to demonstrate medium ISDN

(Integrated Services Digital Network—1.5 Mbps) and broadband ISDN (150 Mbps) rate digital communications among small Earth terminals that cannot be economically interconnected by fiber lightguide trunks and also provide an overflow and alternative routing capability to carry the same primary rates that the fiber light guides carry for a switchable multiple access/multidestination off loading of terrestrial facilities, as well as restoration capacity during fiber light guide outages. Key ACTS technologies are:

- Use of multiple hopping up and down beams on the satellite to achieve high uplink G/T ratio and high downlink EIRP operation that makes possible high bit rate interconnectivity among very small aperture Earth terminals.
- Use of onboard demodulation and remodulation in combination with onboard decoding and recoding to achieve maximum efficient use of the onboard power resource and to provide adaptive compensation of rain fade induced impairments.
- Use of onboard baseband switching to permit flexible rerouting of traffic between the uplink and downlink beams. In the ACTS, this switching is done in increments of 64 kilobits per second (kbps), the standard primitive switching unit used in modern telephone terrestrial circuit switched telephone systems. Thus, ACTS is a switching center in geostationary satellite orbit, a concept that represents one of the most effective applications of satellites in their best role of multiple-access, multiple-destination communications. Control of the onboard switch connections is performed from the ground via a command link from a single network control station and is based on demands for connection placed from the Earth terminals over order wires carried over the system.
- Use of a ground network of TDMA Earth terminals synchronized to the onboard satellite switch and the hopping beams. The system is capable of achieving fully variable demand assignment of the individual 64-kbps digital communications. Higher bit rates are achieved by assigning capacity between stations in integer multiples of 64 kbps.

- Use of 30/20-GHz technology for commercial satellite communications. This promises to open up yet another portion of the RF spectrum for regular commercial satellite communications use. Over a decade ago, the joint US/Canadian communications technology satellite tested a large-aperture, high-EIRP satellite beam at 14 GHz up and 11 GHz down (in the K_u-band part of the RF spectrum), which, at the time, was considered revolutionary and was responsible for stimulating the now vigorous worldwide use of the 14/11- to 14/12-GHz band.

The Soviet literature provides no indication of Soviet activity on advanced developments of the nature of those outlined above for the ACTS—with the possible exception of the 30/20-GHz frequency band.

There are other advanced developments in the West of which the Soviet Union must certainly be aware, but on which there is no apparent Soviet activity. These include:

- Onboard microwave switching among beams such as currently used on INTELSAT-VIs to interconnect six beams operating at 6/4 GHz. The signal switched is 120 Mbps TDMA.
- Onboard demodulation and remodulation combined with memoryless baseband switching of 150-Mbps TDMA carriers among six 0.5°-beam-width spot beams now being implemented for interconnecting beams on the Italian ITALSAT system. Like the ACTS, this system also uses the 30/20-GHz RF band.
- Digital implementation using digital signal processing chips, VLSI components in silicon or gallium arsenide technology of switches, modulators, demodulators, demultiplexers, and multiplexers. Such implementation is now vigorously being pursued in the United States, Western Europe, and Japan, for both terrestrial and satellite onboard use in commercial and military applications.

- Multibeam satellite antennas using multiple horn feed arrays of the type now used on commercial satellites such as the INTELSAT-V, -VI, and -VII at 6/4 GHz and the ITALSAT and ACTS at 30/20 GHz.
- Solid-state power amplifiers for onboard application up to 20 W at 4 GHz, 4 W at 11/12 GHz, 1 W at 20 GHz, and 0.5 W at 40 to 60 GHz.
- Digital implementation of high-speed fast Fourier transform (FFT) devices for frequency domain demultiplexing and remultiplexing filter banks. The speeds of digital arithmetic processors and the capacities of high-speed memory devices available in the United States, Europe, and Japan are now approaching the level where processing bandwidths as great as 100 MHz for demultiplexing carriers on board the satellite to their baseband spectrum and remultiplexing them to switch channels and rearranging the locations of carriers in the RF spectra between multiple up and down beams.

Although no evidence of Soviet advanced communications satellite onboard technology was identified in the literature, a mature Soviet technology appears to exist for use of digital computers on board aircraft. A book entitled *On-Board Digital Computers and Computer Systems* by Matov et al. (1988) is devoted to the fundamentals of the use of digital computers for algorithmic synthesis, aircraft monitor and control, data gathering, data processing, and decision making. The authors appear to be associated with the Khar'kov Aviation Institute, and the text is probably used in a training course. This book is said to be the first of its kind published in the Soviet Union.

Soviet scientists are certainly aware of the advantages that advanced onboard processing will bring to satellite communications, as evidenced in a paper by A. G. Zyuko (1988) entitled "Methods of Increasing Efficiency of Satellite Communications Systems." The author writes:

The efficiency of digital satellite communications systems may be increased significantly when signal processing and switching is organized on board the satellite. Introducing onboard signal regeneration equipment provides an additional increase in energy efficiency. This makes it possible to optimize the "up" and "down" lines independently of one another by using different coding and modulation versions in these lines. Moreover, when used in conjunction with modern antennas (multibeam antennas with electron

beam switching, antenna arrays, etc.), digital processing devices make it possible to use a spatiotemporal channel separation method in which radio channels are switched with high precision and both of the system's efficiency indicators are increased.

4. Optical Signal Processing

Optical signal processing is well advanced in the Soviet Union. The book by Voskresenskiy et al. (1986) contains well-developed optical signal processing techniques applicable to a wide range of applications other than antenna arrays.

The signal processing methods addressed in this book indicate a high degree of sophistication applicable to beam forming based on optical processing techniques. The authors observe that digital signal processing methods, which have been applied to lower bandwidths at lower frequencies for sonar, cannot be applied to wider bandwidth radar signal processing, because the digital computers would be too large and unwieldy. Therefore, optical signal processing techniques are preferred. Digital signal processing methods are far more accurate than optical processing methods, but optical processing is still preferred for broadband applications.

The technology represented by this work is not only applicable to the antenna array problem, but also to the implementation of FFT spectrum analyzers—digital as well as analog—needed for demultiplexing of RF signals. Thus, it is likely that Soviet researchers have the capability to design FFT communication signal processors for demultiplexing and demodulation up-link signals by optical means. Furthermore, they understand it can be accomplished by digital means if sufficiently high-speed processors can be obtained.

Optical information processing methods make it possible to simultaneously analyze large two-dimensional bodies of information in real time, which is their main advantage over digital information processing methods. However, as far as flexibility of realized mathematical operations and algorithms and accuracy of calculations are concerned, optical information processing methods are inferior not only to digital computers, but also to analog electronic computer equipment. There are two ways to overcome this lack of universality of optical processors. The first is to develop hybrid optoelectronic computer systems, consisting of a universal computer and an optical special processor, which make it possible to

combine the fast speed and productivity of optical information processing methods with the computers' flexibility and accuracy of calculations. The second is to use problem-oriented analog optical processors for solving highly specialized problems. An additional, promising method is the development of optical computers that process digital information and are based on optoelectronic devices.

5. Missing Technologies

A number of technologies conspicuously are missing from the Soviet literature. There is likely some effort in these areas but, due to their sensitive nature, no work is being published. These areas include the following:

- analog MMICs;
- solid-state power amplifiers;
- digital VLSI;
- TWT linearization circuits;
- onboard microwave switching;
- onboard baseband switching;
- onboard lightweight channel filters;
- onboard demodulation/modulation;
- onboard digital signal processing;
- nulling antenna systems for anti-jam (AJ);
- onboard spectrum despreading for AJ;
- agile frequency converters; and
- AJ waveforms.

G. SOVIET AND US MILITARY COMMUNICATIONS SATELLITES

Future directions for US military satellite communications systems include the following areas:

- increased capacities;
- improved interference/detectability protection against jammers, interceptors, and propagation disturbances;

- autonomous configuration control (satellite-based routing controllers, rapid user-initiated reconfigurations);
- smaller, lighter-weight implementations;
- flexible, rapid launch capabilities; and
- inter-satellite links (crosslinks).

These goals are being pursued through a number of enabling techniques, including antenna directivity, higher frequencies, spectrum spreading, and signal processing, as indicated in Table IV.1. Even interference-resistant spread-spectrum modulations are being considered to mitigate mutual interference in future mobile commercial communications satellite systems. As described below, the material reviewed by the panel indicates that Soviet researchers are also actively investigating many of these enabling techniques. In the remaining areas, future activities can be anticipated as the exchange of information between the United States and the Soviet Union becomes freer.

<p style="text-align: center;">Table IV.1 SOME ANTICIPATED APPROACHES</p>				
Enabling Techniques/Goals	Antenna Directivity	Higher Frequencies	Spectrum Spreading	Signal Processing
Increased capacity	x	x (44/20 GHz)		x
Improved interference/ detectability protection	x	x (44/20 GHz)	x	x
Autonomous configuration control				x
Lighter-weight implementations				x
Crosslinks		x (60 GHz; optical)		x

1. Antenna Directivity

Satellite communication systems are moving increasingly in the direction of directive antennas on board the satellites. As shown in Figure IV.1, the use of directive antennas allows a given data rate to be transmitted from much smaller terminals. This helps contain the cost of the terminal segment and allows more mobile or transportable terminals to be developed. In US systems, mechanically steered spacecraft reflector antennas are currently being utilized and electronically pointed antennas are emerging.

Figure IV.1
Antenna Directivity

Soviet commercial systems commonly use antenna directivity to increase a communication payload's capabilities (Kantor, 1988; Varbanskiy, 1989). Soviet directive antennas are typically mechanically pointed reflectors, but the advantages of the use of electronically pointed directive antennas such as multibeam and array antennas in contributing to the efficiency of a payload are recognized (Zyuko, 1988; Voskresenskiy et al., 1988). The "Arkus" communications satellites, scheduled for first launch in 1993, will have active phased arrays for receiving and transmission in the 1.6/1.5-GHz band (Radimov and Mikolenko, 1990).

2. Frequency Considerations

US military satellite communications systems are moving to higher frequencies, the high SHF and low EHF bands (20 and 44 GHz), to utilize the associated large bandwidth allocations for increased capacities and/or increased interference and detectability protection, despite the need for increased link margins to counter attenuation due to wet weather as shown in Figure IV.2.

Future AJ/Covert Systems Using EHF for Increased Capacity and Robustness; Incorporating Sufficient Link Margin for Weather

Figure IV.2
Frequency Considerations

In the early 1980s, Soviet researchers performed propagation measurement experiments in the upper SHF and EHF bands (11, 14, 20, and 30 GHz) (Bykov et al., 1983). Soviet plans for geosynchronous satellite communications systems of the 1990s include the use of these higher frequencies in their Luch (14/11 GHz) and Tor (44/20 GHz) systems,² for fixed and mobile communications, respectively. Based on the Soviet published literature, the extent to which these bands will be used for increased capacity versus increased protection is not known. However, if such systems are developed with primarily small terminals (≤ 0.6 -m diameter antennas), the emphasis is probably on increased protection. Correspondingly, a system of large terminals would indicate increased capacity as a goal.

3. Signal Processing

US military satellite communications systems and, in some cases, commercial systems are moving in the direction of signal processing on board the satellite. As shown in Figure IV.3, signal processing can provide capacity and interference protection improvements by reducing noise and interference sources in the uplink signal before transmission on the downlink. Thus, more of the downlink power is devoted to user signals as shown. For protection from interference, two frequently utilized signal processing techniques include spectrum spreading and diversity coding. Figure IV.4 shows two common methods of spectrum spreading, direct sequence spreading, and frequency hopped spreading, as well as the use of encoding and interleaving to form a bit stream for transmission. Advanced US systems utilize many of these forms of signal processing, including diversity coding (both on an end-to-end and on a link-by-link basis), spectrum spreading, and onboard demodulation/remodulation.

Soviet researchers are investigating a wide range of signal processing applications, including data compression techniques, efficient modulation and coding combinations, onboard satellite switching and signal regeneration, channel distortion compensation, and the use of digital signal processing algorithms to help protect signals in the presence of different types of noise sources (Zyuko, 1988).

² N. L. Johnson, *The Soviet Year in Space 1987*, Colorado Springs, Colorado: Teledyne Brown Engineering, January 1988.

Figure IV.3
Advantages of Satellite Signal Processing

In the area of modulation and coding, Soviet workers have been investigating advanced techniques for use in obtaining more efficient communications in their satellite systems.³ Goals in these efforts are to provide greater throughput per unit bandwidth, to operate with lower signal-to-noise ratios, to provide both greater throughput and higher energy efficiency, and to provide protection in the presence of interference. Typical modulations considered include constant envelope techniques such as binary, quaternary, and 8-ary phase shift keying (BPSK, QPSK, 8-PSK), bandwidth efficient approaches such as minimum shift keying and continuous phase frequency shift keying (MSK, CPFSK), and hybrid amplitude/phase modulations such as 16-QAM. Coding techniques include primarily

³ Banket, 1988; Zyuko, 1988; Kantor, 1988; Banket et al., 1987; Ipatov et al., 1990; Morozov, 1989; Portnoy and Ankudinov, 1984.

convolutional codes with a variety of code rates (from rate 1/8 to rate 8/9) and constraint lengths (ranging to 11 or more) along with either threshold or Viterbi decoding. For some applications, block codes are also considered (Portnoy and Ankudinov, 1984). In addition to separable modulation and coding systems, Soviet researchers are also investigating combined modulation and coding systems in which the demodulation process is a part of the decoding procedure and is performed using Viterbi-type algorithms (Zyuko, 1988; Morozov, 1989).

Figure IV.4
Signal Processing for Interference/Detectability Protection

Other forms of signal processing that can provide significant benefits to communications systems in certain environments include spread spectrum techniques. Soviet research includes development of subsystems for both direct sequence spreading (Zhodzishskiy and Sila-Novitskiy, 1988) and frequency-hopped (Shakhgil'dyan et al., 1983) systems. Either form of spread spectrum pro-

tection could be deployed in the near term using the existing Soviet transponder capabilities (36 megahertz [MHz]) at 4/6 and 7/8 GHz. However, to fully utilize the 1 to 3 GHz of bandwidth, which is potentially available at 44/30/20 GHz, one would expect that frequency hopping would be used. The digital logic speeds and timing requirements associated with ≥ 1 GHz of direct sequence spreading will probably be too difficult, especially for the anticipated level of Soviet digital technology.

4. Autonomous Configuration Control

US satellite communications systems are moving in the direction of satellite-based routing control, as illustrated in Figure IV.5. This approach has the potential for providing more efficient use of system resources and can respond quickly to requests for system reconfigurations.

Figure IV.5
Autonomous Configuration Control

With this type of dynamic, user-initiated control, one can implement effective demand assignment techniques where a large number of terminals share (according to current needs and priorities for service) the resources of a satellite communications system. Also, the spacecraft can be dynamically reconfigured to route individual messages from one or more uplink antennas to different downlink destinations.

No material on Soviet plans for onboard, autonomous configuration control in satellite communications systems was identified. However, Soviet work on network efficiency⁴ and increased Western interactions could lead to such future applications.

5. Lightweight Implementations

US military communications satellite system planning is moving in the direction of incorporating smaller satellites, based on lighter-weight implementations, into the overall architecture. Smaller satellites will result in lower cost space segment increments. They will be able to utilize smaller (perhaps mobile) launch vehicles that utilize rapid launch procedures, which will provide increased survivability. This approach will give the possibility for rapid augmentation of service in critical areas.

There does not appear to be a Soviet interest (based on the published literature) in particularly lightweight payload implementations. The Soviet Union has a number of heavy lift boosters capable of placing large satellites into orbit. Therefore, the Soviets may not at this time perceive a need to reduce satellite weight. However, this could become a trend in the future due to economic considerations.

6. Inter-Satellite Links and Advanced Crosslink Technology

The planning for future US military communications satellite systems is addressing the need for inter-satellite links to provide global connectivity with-

⁴ Portnoy and Ankudinov, 1984; Askinazi, 1984; Gorskiy and Grigor'yeva, 1984.

out ground relays. As shown in Figure IV.6, the use of 60-GHz or optical links is being considered to provide protected crosslinks.

Figure IV.6
Inter-Satellite Links

Soviet researchers have implemented TDRSS-like (14/12 GHz) intersatellite links for data relay using their Satellite Data Relay Network (SDRN) and SSRD-2 systems.⁵ No Soviet literature on plans for 60-GHz or optical crosslinks was identified, but the technologies required are being explored. This is an area to watch for further developments.

⁵ N. L. Johnson, *The Soviet Year in Space 1987*, Colorado Springs, Colorado: Teledyne Brown Engineering, January 1988.

7. Additional Technologies

In addition to the high-leverage communications payload technologies discussed above, Soviet researchers are concurrently investigating advanced components and circuitry for improved filters and demodulators,⁶ advanced antenna systems,⁷ high-power transmitters,⁸ and improved devices.⁹

H. LINK PERFORMANCE POSSIBILITIES

To assess the Soviet potential for increasing satellite communications link throughput to 120 Mbps or above, this section presents some simple calculations of the relationship between link technical characteristics and throughput, using technical characteristics that appear to be comfortably within the Soviet state of the art.

The parameters of interest in a typical satellite communications link are shown in Figure IV.7 and include the transmitting terminal antenna gain and transmit power; the satellite's receive antenna gain, receiver temperature, processing speed or transponder bandwidth, the transmit antenna gain, and the transmitter power; and the receiving terminal's antenna gain and receiver temperature. Based on these types of link parameters, the performance for an example processed link at 7/8 GHz for a satellite in a synchronous altitude orbit is shown in Table IV.2. In this example, a 60-ft/1,000-W terminal and a 3-ft/40-W satellite can support over 1 gigabit per second (Gbps) on both links. As can be seen in this example, the downlink data rate is generally the limiting rate for a satellite communications system due to the lower transmitter power provided in the satellite. These same link calculations have been extended to other satellite and terminal parameters in Table IV.3. On the uplink, the large terminal should be able to support 160 Mbps even into an earth coverage antenna. To achieve this same rate to the large terminal on the downlink requires a more directive beam provided by a 1-ft satellite dish antenna with a 40-W transmitter. With a

⁶ Fedorovskaya, 1989; Smirnov et al., 1989; Andreyev et al., 1989; Abramovich et al., 1989; Rosloniets, 1989; Vernigorov and Pugovkin, 1989; Kulakov et al., 1989.

⁷ Beyder, 1990; Sverdlik et al., 1990; Mar'in and Pachikov, 1989.

⁸ Vanke et al., 1990; Minakova and Panov, 1989; Bugayev et al., 1989; Kolosov et al., 1989.

⁹ Brovkin et al., 1989; Akhmedzhanov and Bozhevol'nyy, 1989; Davyatov et al., 1989.

smaller terminal (20 ft), a 3-ft satellite parabolic antenna would allow a 200-Mbps link to be supported as shown in Table IV.3. Therefore, from a link closure point of view, there is no reason that a modest system, with a 20-ft/1,000-W or larger terminal coupled with a 3-ft/40-W or larger satellite transmission system, could not support a data rate of about 200 Mbps. A similar conclusion can be drawn at EHF (44/20 GHz), where, from a synchronous altitude orbit, a high data rate downlink of over 200 Mbps could also be supported with a 20-ft terminal and a modest space segment (2 ft/25 W) as shown in Table IV.4. Table IV.5 shows a calculation for a link from a low-altitude mission satellite directly to the ground, and Table IV.6 contains representative parameters if the link from the mission satellite is routed through a high-altitude relay satellite before being sent to the ground. Based on the values in these link examples, and on the current Soviet terminal and satellite antennas and transmitter parameters, it would seem that increased channel data rates in excess of 100 Mbps are within Soviet capabilities. To achieve this performance, wider bandwidth transponders must also be deployed; however, this does not seem to be a significant challenge.

Figure IV. 7
Satellite Link Options

Table IV.2
SHF LINK CALCULATION*

	Uplink		Downlink	
TX power (dBW)	1,000 W	30.0	40 W	16.0
Antenna gain (dBi)	60 ft	61.3	3 ft	34.5
Losses (dB)		-5.0		-2.0
Free space path loss (dB)	8.15 GHz	-202.8	7.5 GHz	-202.1
Minimum margin allowance (dB)	0.998	-3.0		-3.0
1/Boltzmann's constant (dB Hz K/W)		228.6		228.6
Antenna gain (dBi)	3 ft	35.2	60 ft	60.5
1/System temperature (dB/K)	600°K	-27.8	400°K	-26.0
Losses (dB)		-1.0		-3.0
E_b/N_0 (dB)	1E-05 QPSK	-10.0	1E-05 QPSK	-10.0
Losses (dB)		-2.0		-2.0
Data rate (dB Hz)		103.5		91.6
Data rate		22 Gbps		1.4 Gbps
* Assumes processed channel.				

Table IV.3
SHF LINK EXAMPLES*

Satellite Uplink			
Terminal	3 ft, 600°K	1 ft, 1,000°K	EC†, 1,000°K
60 ft, 1 kW	22 Gbps	2.5 Gbps	160 Mbps
20 ft, 1 kW	3.1 Gbps	350 Mbps	22 Mbps
Satellite Downlink			
Terminal	3 ft, 40 W	1 ft, 40 W	EC, 40 W
60 ft, 400°K	1.4 Gbps	160 Mbps	20 Mbps
20 ft, 400°K	200 Mbps	22 Mbps	2.8 Mbps
* Assumes processed channel. Assumes no bandwidth constraints. Dishes provide point coverage. † EC = Earth coverage.			

Table IV.4
EHF LINK CALCULATION

	Uplink		Downlink	
TX power (dBW)	1,000 W	30.0	25 W	14.0
Antenna gain (dBi)	20 ft	66.5	2 ft	39.8
Losses (dB)		-4.0		-2.0
Free space path loss (dB)	44.5 GHz	-217.6	20.7 GHz	-210.9
Minimum margin allowance (dB)	0.99	-12.0		-5.0
1/Boltzmann's constant (dB Hz K/W)		228.6		228.6
Antenna gain (dBi)	2 ft	46.5	20 ft	59.8
1/System temperature (dB/K)	1,000°K	-30.0	500°K	-27.0
Losses (dB)		-1.0		-2.0
E_b/N_0 (dB)	1E-05 DMSK	-10.7	1E-05 DMSK	-9.1
Losses (dB)		<u>-2.0</u>		<u>-2.0</u>
Data rate (dB Hz)		94.3		84.2
Data rate		2.6 Gbps		260 Mbps

Table IV.5
LOW-EARTH ORBIT LINK CALCULATION*

TX power (dBW)	20 W	13.0
Antenna gain (dBi)	2 ft	31.0
Losses (dB)		-2.0
Free space path loss (dB)		-175.5
Minimum margin allowance (dB)		-3.0
1/Boltzmann's constant (dB Hz K/W)		228.6
Antenna gain (dBi)	20 ft	51.0
1/System temperature (dB/K)	400°K	-26.0
Losses (dB)		-3.0
E_b/N_0 (dB)	1E-05, QPSK	-10.0
Losses (dB)		<u>-2.0</u>
Data rate (dB Hz)		102.1
Data rate		1.6 Gbps

* Assumes 7-GHz downlink and 400-nmi orbit.

Table IV.6
RELAY LINK CALCULATION*

	LEO → GEO		GEO → GND	
TX power (dBW)	20 W	13.0	20 W	13.0
Antenna gain (dBi)	4 ft	42.3	4 ft	41.0
Losses (dB)		-3.0		-4.0
Free space path loss (dB)		-207.8		-206.2
Minimum margin allowance (dB)		-1.0		-4.0
1/Boltzmann's constant (dB Hz K/W)		228.6		228.6
Antenna gain (dBi)	16 ft	54.4	60 ft	64.6
1/System temperature (dB/K)	600°K	-27.8	400°K	-26.0
Losses (dB)		-2.0		-3.0
E_b/N_0 (dB)		-10.0	1E-05 QPSK	-10.0
Losses (dB)		<u>-2.0</u>		<u>-2.0</u>
Data rate (dB Hz)		84.7		92.0
Data rate		300.0 Mbps		1.6 Gbps

* 14-GHz uplink from LEO satellite to relay at synchronous altitude.
12-GHz downlink to ground.

I. COMMUNICATIONS LINK LIMITATIONS

It has been shown that very high rates can be transmitted from space to ground, from ground to ground through a relay satellite, and from space to ground through a relay satellite. The Soviets apparently have no immediate plans to communicate at frequencies above 15 GHz. Furthermore, satellite antennas used for communications are relatively small at these higher frequencies (for example, 0.9 m) and power amplifiers at these frequencies are on the order of 20 W. With this information, it is possible to determine typical data rates that can be expected on space missions like Radioastron.

- Consider the Radioastron mission at an altitude of 77,000 km, transmitting data to a 10-m ground station. Radioastron is equipped with a 0.9-m antenna and 20-W power amplifier at 14-GHz transmit frequency. With these parameters, and typical losses and margins for rain, the expected data rate would be 150 Mbps at 10^{-5} bit error probability.

- Next, consider an LEO equipped with a .9-m antenna and a 20-W power amplifier at 14 GHz. This satellite transmits data to a relay satellite in a geostationary orbit. The relay satellite is also equipped with a .9-m antenna. Under these circumstances, the link can support 12 Mbps at 10^{-5} bit error rate without forward error control coding (FEC), 36 Mbps with FEC.

These calculations show that with typical Soviet published technology, the high-altitude Radioastron should be able to transmit 128 Mbps to a large ground station. Furthermore, when these technologies are used in the relay satellite example, the communications link can support 12 Mbps without the use of error control coding. If the Satellite Data Relay Network is upgraded to a US Tracking and Data Relay Satellite System capability, that is, to 4.5-m antennas on the geostationary relay satellites, then this link theoretically could support data rates as high as 300 Mbps, and 900 Mbps with FEC.

J. KEY SOVIET RESEARCH PERSONNEL AND FACILITIES

Key Soviet researchers in the area of satellite communications payloads and their general areas of interest are listed below.

V. L. Banket	Modulation and coding
A. G. Zyuko	SATCOM systems
L. Ya. Kantor	SATCOM systems
A. Varbanskiy	SATCOM systems
V. M. Dorofeyev	Interference and systems; modulation and coding
S. V. Borodich	Interference and systems
V. V. Timofeyev	SATCOM systems

In addition, the following officials and organizations are involved in the development and deployment of Soviet satellite communications systems:

M. F. Reshetnev	Head, Scientific Production Association of Applied Mechanics, Krasnoyarsk (which has developed most of the current Soviet communications satellites)
A. Kozlov	Deputy to M. F. Reshetnev
Yu. Zubarev	Deputy Minister of Communications
Yu. P. Semenov	Head, Energiya Scientific Production Association/NPO (which is advocating the 36-ton satellite)
B. Ye. Chertov	Deputy to Yu. P. Semenov.

K. SOVIET TECHNICAL LITERATURE

This chapter focuses on the communications payload technology used on board the satellite for transponding the communications radio frequency (RF) signals from the up to down links. Several thousand article titles, two books, and numerous abstracts and summaries were reviewed. The following Soviet journals were principal sources: *Radio Engineering and Electronic Physics*, *Radio Electronics and Communications Systems*, *Telecommunications and Radio Engineering*, *Electrical Engineering*, and *Radiophysics and Quantum Electronics*. Numerous abstracts and the contents of two books—*Satellite Communications and the Problem of the Geostationary Orbit* (Kantor and Timofeyev, 1988), and *Radio-Optical Antenna Arrays* (Voskresenskiy et al., 1986)—were reviewed. A survey of the published Soviet literature revealed no direct references to technical characteristics of satellite communications payloads. At best, based upon the titles and abstracts of technical articles and on the external satellite communications system properties, one could only assume what the onboard technology might be. The book by Kantor and Timofeyev (1988), and both the 1987 *World Satellite Almanac* and 1990 *World Satellite Almanac* (Mark Long, Indianapolis: Howard Sams & Co.) were valuable sources.

L. PROJECTIONS FOR THE FUTURE

As the Soviet Union strives toward more development, the capabilities of its satellite communications systems can be expected to continue to increase. Future

Soviet satellite communications payloads will reflect this evolution through the ability to support increased data rates and the incorporation of advanced directive antennas, circuitry, and signal processing and routing techniques, as well as the utilization of higher frequencies. These trends should occur in both commercial (that is, civilian) and military-oriented communications payloads.

The atmosphere of budget cuts for Soviet defense and space organizations is leading to open competition between Soviet scientific production associations (NPOs) for communications satellite business, including collaboration with Western companies. One example of future possibilities involves the proposal by some Soviet space officials from NPO Energiya for a very large satellite that would support eight television channels, 16 stereo audio channels, and more than one million telephone circuits (Kamnev et al., 1989).¹⁰ As another example, Soviet NPOs Radio and Applied Mechanics have announced collaboration with the German firm ANT Bosch Telecom to develop a new communications satellite designated "Romantis."

The technologies necessary for the implementation of advanced communications satellite systems will come from a combination of internal developments and the acquisition of Western capabilities (which are evolving in similar directions). With the current improvements in East-West relationships, this latter avenue may become particularly significant, as in the example of "Romantis." One form in which such acquisitions could materialize is through the merging of the Soviet Intersputnik communications satellite system with the international INTELSAT system. This merger could lead to the Soviet Union being able to purchase and launch Western communications satellites for "commercial" purposes. The Soviets could be expected to continue to build and launch their military satellite communications systems as they do today, but perhaps with the infusion of Western technology from commercial enterprises.

¹⁰ Lon Rains, "Soviets Test Waters for Mammoth Satellite," *Space News*, 15-21 October 1990.

CHAPTER IV: COMMUNICATIONS SATELLITE PAYLOAD TECHNOLOGY

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3. Signal Processing (Digital and Analog)
4. Antennas
5. Microwave Filters
6. Propagation
7. Microwave Circuits
8. Optical Devices
9. Solid-State Techniques and Devices
10. Microwave Integrated Circuits
11. Coding and Modulation
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13. Surface Acoustic Wave Devices
14. Satellite Communications

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CHAPTER V

POWER GENERATION ON SPACECRAFT

A. SUMMARY

Power generation on spacecraft can be accomplished by means of solar generators, nuclear generators, or chemical generators. Solar generators are employed on most spacecraft; nuclear generators are employed in special cases. The Soviet Union has used all types of generators. Chemical generators are employed as secondary power sources.

The Soviet Union has launched communications satellites since 1965, and currently has about 80 communications satellites in operation. These satellites all use solar-power generators with power levels of 0.6 to 3.0 kilowatts (kW). The Soviet space station Mir has solar power generators which, in combination, provide 11 kW of primary power.

Solar generators are based on the direct conversion of solar radiation into electricity by means of photovoltaic cells. The amount of power generated is directly proportional to the area of the solar panels that intercept the sunlight. For this reason, the power generated by a spacecraft can be increased in a modular fashion to any desired amount, limited only by the capabilities of the launch vehicle's ability to place additional weight in orbit.

The Soviet Union also employs nuclear generators, primarily on military ocean surveillance spacecraft (satellites with nuclear generators are less vulnerable to damage if attacked than those without nuclear generators). More than 30 such satellites have been launched. Currently available power levels are 10 kW for nuclear power sources.

With respect to the capabilities of future Soviet spacecraft programs, there is no inherent limitation to the increase in spacecraft power. Both solar and nuclear generators can be provided with increased power levels, providing 100 kW or more in primary power, if such power levels should be needed. In this respect, the Soviet launch vehicle capabilities will be an important asset.

The Soviet Union is currently negotiating joint venture programs with Western aerospace companies in order to improve the payload capabilities and lifetimes of its communications satellites. In these negotiations, it is foreseen that the structure for the solar generators would be manufactured in the Soviet Union, but solar cells would be procured in the West to achieve longer lifetimes.

Due to the conversion from a centrally planned economy to a free-market economy currently taking place in the Soviet Union and the focus on the conversion from military to commercial applications, the emphasis of the Soviet space program is expected to shift to applications with economic returns, such as commercial satellite programs. In summary, the generation of spacecraft power will not be an impediment to Soviet programs that require the transmission of large data rates.

B. INTRODUCTION

The most widely used technique for generating electric power on spacecraft is direct conversion of solar energy into electricity by means of photovoltaic cells. Many materials display a photovoltaic effect; however, silicon and (less often) gallium arsenide cells are employed.

At the average distance of Sun from the Earth, the radiated solar power is about 1.3 kW/square meter. With a conversion efficiency of only 10 percent, a solar panel of 1 square meter that is oriented perpendicular to the direction to the Sun will produce 130 watts (W) of power. A solar panel contains a large number of individual solar cells, with appropriate series and parallel interconnection to achieve the required output voltage and current, while providing some degree of protection against failure of individual cells.

The total power of a photovoltaic solar electric system can be arbitrarily increased through the series and parallel connection of additional solar panels. The largest Soviet solar power system currently operational in space is that on the Mir space station, which produces 11 kW in primary power. In comparison, current Soviet communications satellites employ solar power generators of 0.6 to 3 kW.

The Soviet Union has also launched satellites with nuclear power generators with electrical power up to 10 kW.

The information presented in this section was obtained in the following fashion:

- The products of an extensive search of the published Soviet/international literature were evaluated.
- A member of the panel visited the Soviet "Conversion 1990" exhibition in Munich on 20-25 April 1990, during which he held discussions with individuals from numerous Soviet organizations involved in the Soviet space programs, including representatives from Intersputnik, Glavkosmos, the Soviet Ministry of Communications, and the Soviet Ministry of General Machine Construction.
- This panel member also visited Moscow in September 1989 and in June 1990, and held discussions with Government officials involved in the Soviet space communications programs.

The relevant information obtained from these sources is presented and discussed below.

C. DISCUSSION

1. General Information

A single 36-megahertz (MHz) bandwidth Soviet geosynchronous satellite transponder can transmit digital data at a rate of 60 megabits per second (Mbps). A combination of two such transponders or a single 72-MHz transponder (if it were available) could handle 120 Mbps, as on INTELSATs-V and -VI. The spacecraft power associated with this transmission is about 200 W. These are typical examples; wide variations of bandwidth and power efficiency can be encountered, depending on the particular transmission system employed. However, the current Soviet capability for the generation of spacecraft power is much larger than that needed for the transmission of 120 Mbps and above.

Since Molniya-1, the Glavkosmos Krasnoyarsk Plant No. 26 of the Applied Mechanics Scientific Production Association (NPO), which is located in Siberia at longitude 92.85°E and latitude 56.05°N, has been building all of the communications satellites launched by the Soviet Union. Academician (member of the Soviet Academy of Sciences) Dr. Mikhail F. Reshetnev has been the director of the Krasnoyarsk-26 Plant since the mid-1960s.

Specifically, the Krasnoyarsk plant builds the spacecraft bus and the communications antennas, and takes delivery of the payload from another plant (NPO Radio) in Moscow, except for the Glonass payload, which is being provided by a plant in Omsk. Glonass is the Soviet equivalent of the US Global Positioning Satellite System (GPS).

The Krasnoyarsk plant builds the power supplies but buys the batteries, which are nickel-hydrogen batteries delivering some 30 to 35 watt-hour/kilogram (whr/kg) of electrical charge per kilogram mass. The Krasnoyarsk plant builds the structure of the solar generators and integrates them, but it buys the cells.

By the end of 1989, Krasnoyarsk-26 had built and successfully launched 92 spacecraft from Baykonur. Krasnoyarsk-26 presently performs 15 to 20 launches per year. In total, the Soviet Union launches a spacecraft every four or five days throughout the year.

Although these numbers suggest that the above-mentioned spacecraft would be built in an assembly line according to blueprints that would remain unchanged within a given series for a long time, this is not so. All of the satellite types are constantly being altered, modified, and gradually improved upon.

Thus, in power supplies, for example, one can find both the "floating bus" spacecraft electrical power conditioning technology, as well as the "fixed bus" on-board power supply system. Occasionally, mention is made in the Soviet literature of a primary and a secondary power supply system. The bus system of the television satellite (KS) UMSS-330C, with its 500-kg payload consuming

3,000 watts, is laid out for a voltage of 27 ± 0.8 volts (Western satellites presently operate at approximately 50 volts, and tend toward even higher voltages).

The Western technique of leaving excess electrical power in the solar generator, as opposed to bringing it into the spacecraft onboard power system with the need of burning it in shunts (and then having to get rid of the heat), is not implemented in Soviet spacecraft. Otherwise, the (analog) control circuitry of Soviet power systems appears to be similar to that of the West.

A bearing and power transfer assembly (BAPTA) also has been developed for a 13-year operational mission. It can rotate with up to 6.5 degrees/minute with a tracking tolerance of 1.5 degrees, thereby transferring 640 amps at 100 volts, or 32-kW effective power.

2. Gorizont Solar Generator

The solar generator of the Gorizont satellites (Figure V.1) appears to be similar to those designed in the West. The rectangular panels are vertically oriented (as opposed to the horizontally oriented Western products), and there are only two panels (as opposed to the three or more panels used in most Western satellites).

The inner panel shows small auxiliary (baby) panels attached to its upper and lower ends. These sub panels are the same width as the mother panel but extend only to one-fifth of its height, so that they add 40 percent to the area of the mother panel, increasing it to some 140 percent.

The outer panel (sister panel) is the same height as the mother panel. It does not have subpanels, and its width is 137 percent that of the inner panel. This is unusual in Western layouts, where all panels are generally identical in size. However, with this design, the outer panel obtains the same area as the inner panel supported by the two baby panels.

With this near quadratically shaped solar generator, nearly all of the dynamic stability problems encountered with "high-wingspan" solar generators of narrow width (and associated higher characteristic frequencies with which these "high-

wingspan" generators tend to swing as a reaction to even the minutest of spacecraft maneuvers) have been cleverly avoided.

Figure V.1
The Gorizont Communications Satellite

3. Solar Power Plant for the Mir Space Station

The earlier space station, Salyut, had three solar cell arrays, each with an area of 20 square meters. At launch, Mir was equipped with only two arrays, each with an area of 38 square meters, for a total area of 76 square meters. However, Mir (Figure V.2) was equipped with an attachment for a third solar array for later addition.¹ The efficiency of the system was increased through the use of gallium arsenide cells instead of the silicon cells used earlier (Fedorov, 1986). The increase in power was 42 percent (*Sotsialisticheskaya industriya*, 1984). The third panel was installed later by astronauts (*Sovetskaya Rossiya*, 1987). The new panels differed from the earlier panels in the use of cover glass for protection and a graphite fiber structure for lighter weight. Sensing devices were included to identify causes of solar panel degradation such as micrometeorites, charged particles, and gases from spacecraft engines (*Izvestiya*, 1988). The third panel has an area of 24 square meters and provides a power output of 2.4 kW (Kuznetsov, 1987). The combination of the three panels, a total area of 100 square meters,

¹ Dietrich Haeseler, "Design Features of the Mir Space Station," *Spacecraft*, 28, 11(1986), 384-385.

provides a power output of approximately 11 kW,² or approximately 110 W/square meter.

Source: N. L. Johnson, *The Soviet Year in Space 1987*, Colorado Springs, Colorado: Teledyne Brown Engineering, 1988, p. 104

Figure V.2
The Mir Space Station

Soviet researchers project that manned space stations following the current Mir will be provided with 150 to 200 kW of solar electric power, possibly as early as the year 2000.

4. Assessment of Soviet Solar Power Technology

Generally, Soviet solar panel structures are of good mechanical quality with resulting good weight efficiency. Soviet cells do not appear to yield life expectan-

² "Soviet Station Mir Be Enlarged Altitude Power Calculations," *Flug Revue-Flugwelt International*, 12(1987), 7.

cies common in the West which, however, are a good match with their "inclination-uncorrected spacecraft," whose life expectancy is three years.

The conversion efficiency of the Soviet cells (in watts per square meter) is underdeveloped (less than two-thirds of the typical Western figures), because, in the past, mass has not been considered a pertinent parameter in the Krasnoyarsk spacecraft design. Thus, low watts-per-square-meter performance has been compensated for by larger panels. INTELSAT-IV type mass-per-power numbers (150 g/W) have been flown until recently, but the INTELSAT-V figure of 40 g/W has been achieved in the Ekran television satellite system solar generator (corresponding Western figures today are 20 g/W).

Western "ultra-light panels" exhibited 45.0 W/kg in the late 1960s. The European OTS/MARECS showed 17.7 W/kg in the early 1970s. The European INTELSAT-V panel delivered 24.5 W/kg, and the US INTELSAT-VI delivered 12.6 W/kg (a Hughes product) approximately 10 years later. The German KFS/Kopernikus produces 36.0 W/kg, EUTELSAT-II produces 42.1 W/kg, Mark-IV produces 50 W/kg, and SCS-1 produces 38.4 W/kg.

Thus, the 11-kW solar generator proclaimed by designers of the Mir space station seems realistic. Anyone familiar with spacecraft manufacture in the West who has visited a Soviet satellite plant facility will attest to the high standards of quality and excellent workmanship performed there (particularly in the mechanical engineering sector), as well as the distinct dedication of Soviet workers in the space industry.

5. Solar Power and Spacecraft Longevity

The Soviet space program has resulted in spacecraft with lower reliabilities and shorter life expectancies than those of the West. Typical Soviet communications satellites have life expectancies of only three years, whereas US satellites have life expectancies of 10 years or more. The short life expectancy of Soviet satellites requires more frequent launches of replacement satellites.

The Soviet space organization has recognized the need for longevity to attain economies of scale in the transponder cost of communications and broadcast

satellites. The new (KA) MSS-2500 spacecraft bus has been designed by NPO Applied Mechanics for a mission life expectancy of 13 years. Redundancy schemes have been devised and documented (even if somewhat different from those in the West). The concept of single-point failure has long been realized. The satellite is designed to function autonomously for 30 days without any control from the ground.

One of the limitations on spacecraft useful life is the longevity of the solar cells, which degrade due to radiation damage in space. It is likely that the Soviets will use foreign (most probably German) solar cells for these future long-lived satellites.

6. Space Power Stations

Several Soviet articles discuss the prospect of implementing large-scale generation of solar electricity in space for transmission to Earth; however, none of these articles seriously proposes their implementation.

A 10-GW system using an area of 100 square kilometers and having a mass of 100,000 tons is proposed. Supplying only 10 percent of the total electricity requirements of the Earth in this fashion would have serious impact on the ecology (Avduyevskiy et al., 1981).

A later article mentions a 5-GW system with a solar panel area of 50 square kilometers (Zaytsev, 1988). Thin-film solar cells are proposed to reduce mass and launch costs.

7. Nuclear Generators

The Soviet space program has included the use of nuclear power generators since the launch of Kosmos-198 in 1967. Nuclear research (including nuclear power supplies such as plutonium RTGs for space applications) is being conducted at Krasnoyarsk Plant No. 45. Soviet researchers have developed two reactor types for use in space—the Romashka (Kucharkin et al., 1990) and the Topaz (Wetch et al., 1990).

The Romashka generator uses a nuclear reactor to produce heat and converts a portion of the thermal energy into electricity through the use of silicon-germanium thermocouples. However, it is low powered and has a low conversion efficiency (about 2 percent) with a net electric output of less than a kilowatt. The Topaz also uses a nuclear reactor to produce heat energy, part of which is converted into electricity by the thermionic principle. An emitter is heated to about 1,500 K, at which temperature electrons leave freely. Within the short distance of a few microns, a collector is maintained at much lower temperature, and electrons flow to it. It is of higher efficiency (about 12 percent), and has an electric output of up to 10 kilowatts.

The United States is considering buying a Topaz and re-engineering it to give the United States a short-cut to a nuclear power module for space missions.

Following the accidental reentry of RORSATs in Canada and over the Indian Ocean, there has been much negative publicity regarding the safety of these devices (the reentries apparently occurred because the system intended to boost the reactor into a higher orbit had failed). Since then, an additional safety feature has been introduced: separation of the radioactive material from the satellite prior to reentry to ensure that it is completely dispersed over wide areas.

Both Soviet and US scientists have urged a complete ban on the use of nuclear reactors for Earth-orbiting satellites, while permitting them for deep space exploration. By 1988, the United States had launched 22 satellites with radioisotope thermoelectric generators and one reactor-powered spacecraft. The Soviet Union has launched more than 30 reactor-powered RORSATs. Approximately 10 to 20 percent of these missions have suffered failures or accidents.³

8. Soviet Individuals Contacted

Soviet researchers who were contacted for various discussions are listed in Table V.I.

³ Theresa M. Foley, "Soviet, US Scientists Urge Ban on Nuclear Powered Satellites," *Aviation Week & Space Technology*, 128, 23(1988), 48.

Table V.1
SOVIET RESEARCHERS CONTACTED

Name	Title	Affiliation
Viktor V. Kuznetsov	Vice Chairman	Glavkosmos USSR, Moscow
Igor V. Malyshev	Engineer	Technounion
Igor D. Alekseyev	Engineer	Technounion
Sergey D. Poudikov	Deputy Director	Soviet Chamber of Commerce and Industry Data Processing Center, Moscow
M. G. Kolobkov	(not available)	Glavkosmos USSR, Space Device Engineering Institute, Moscow
Vladimir I. Bazin	Engineering Expert	Handelvertretung der USSR
Dmitriy Yu. Poletayev	Department Head	Glavkosmos USSR
Albert Kozlov	Vice General Designer and General Director	Applied Mechanics Scientific Production Association, Krasnoyarsk
Boris I. Chirkov	Director General	Intersputnik, Moscow
Alfred Ye. Shestakov	Deputy Minister	General Machine Building Ministry, Moscow
Michal A. Grudzinskiy	Director	All-Union Television Research Institute, Leningrad
Aleksandr V. Samoylenko	Engineer, Electronic and Test Equipment Group	Manufacturing Engineering Research Institute, Moscow
Lev Ya. Kantor	(not available)	Radio Scientific Research Institute
Viktor M. Tsirlin	(not available)	Radio Scientific Research Institute
Aleksandr P. Rodimov	General Director	Scientific Industrial Corporation "Astra," Moscow
Yuriy G. Kalyan	President	Assn. for Cooperation Between Soviet & Foreign Organizations, "Mir," Moscow
Mikhail F. Reshetnev	General and Research Director	Glavkosmos USSR, Moscow

Table V.1
SOVIET RESEARCHERS CONTACTED (cont'd.)

Name	Title	Affiliation
Vladimir V. Tsimaylo	Director, Group Leader of Kosmos	"Kosmos"
Yevgeniy Korchagin	Department Head	Applied Mechanics Scientific Production Association, Krasnoyarsk
Vladimir Khalimanovich	Chief Designer	Applied Mechanics Scientific Production Association, Krasnoyarsk
Vitaly I. Khokhlov	Chief of Main Scientific and Technical Administration	Soviet Ministry of the Communications Industry, Moscow
Svetlana O. Volkova	Economist	"Licensintorg," Moscow
Vladimir Bartenev	Department Head, Professor	Applied Mechanics Scientific Production Association/Krasnoyarsk State University, Krasnoyarsk
Albert Kozlov	Vice General Designer and General Director	Applied Mechanics Scientific Production Association, Krasnoyarsk

D. PROJECTIONS FOR THE FUTURE

With the conversion of the centrally planned economy to a free-market economy, the Soviet Union will begin to measure the disproportionate amount of effort spent on the space programs and will continue to reduce the military portion of this effort and concentrate more on commercial applications, such as communications satellites. Therefore, nuclear power generators will become less important, and more emphasis will be placed on the improvement of solar power generators.

The Soviet Union will begin to work with Western companies to improve the reliability and the overall life expectancy of its satellites, including the solar power generators. The Soviet capability for construction of the structure and other mechanical elements is excellent, but help is needed to improve the life

expectancy and reliability of solar cells. This help will be obtained from Western sources.

As the result of Western cooperation, the Soviet Union will be able to fly solar electric power systems in the multi-kilowatt range with high reliability and long life expectancy, fully adequate for transmission rates of 128 Mbps at normal transmission frequencies, for example, 12-GHz downlinks from space missions such as the Radioastron.

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CHAPTER V: POWER GENERATION ON SPACECRAFT REFERENCES

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CHAPTER VI

EARTH TERMINAL RESEARCH

A. SUMMARY

The Soviet Union does not appear to be placing much emphasis on improved Earth terminal technology beyond routine antenna performance enhancements and research into better production techniques for components such as low-noise amplifiers (LNAs) and traveling wave tubes (TWTs) (Zyuko, 1988). Instead, Soviet researchers are putting greater efforts on improved coding and modulation techniques and on exploiting the heavy launch capability to permit the deployment of much larger (30-m) satellite antennas in space. The larger antennas will have a significant impact on the overall system performance, because they allow a simplified ground station design (that is, smaller antennas and cheaper receivers can be used to achieve the same link margin, and less powerful transmit high-power amplifiers [HPAs] are needed to provide the uplink with adequate carrier levels). The large spacecraft antennas will achieve these improvements at the cost of narrower beams and less coverage, which lead to greater terminal operational complexity.

Specific findings on Soviet research include the following:

- The Soviet Union has no Earth terminal (radio frequency [RF] systems and equipment) limitations to transmitting or receiving a signal of 128 Mbps. Soviet researchers have the Earth terminal antenna gain and RF equipment performance characteristics to handle this high data rate.
- The Soviet Union is placing increased emphasis on geostationary Earth orbits (GEOs). Among other reasons for using GEOs will be less need for the sophisticated satellite tracking and hand-over schemes now needed for low-Earth (LEO) and Molniya orbits.
- With the advent of the Soviet heavy launch vehicles, reportedly Soviet researchers are exploring placement of larger (up to 30-m) antennas (greater downlink signal power and less uplink equivalent-isotropic-radiated power [EIRP] required to yield the same carrier-to-noise ratio at

the satellite), more powerful transponders, and multiple-redundant components (greater reliability) on board their spacecraft. This trend could be attributed, in part, to the poor life expectancy of Soviet communications satellites. The benefit afforded by the larger antenna is a corresponding decrease in the cost and complexity of the radio frequency part of the Soviet Earth terminals.

- Aside from several new antenna configurations for the Ekran receive stations (television direct broadcast), Soviet researchers seem to be placing little emphasis on improving their Earth terminal RF technology. This is evident in the lack of LNA and power amplifier (PA) research. Instead, they have decided (with some dissent) to focus their efforts on increasingly sophisticated signal processing and coding to improve signal quality and reduce error rates in their satellite links. This decision is consistent with the aforementioned "quality vs. quantity" shift in Soviet thinking. In addition, there is no evidence that Soviet workers have developed any phased array or conformal type antennas, although they have a good theoretical knowledge of antennas and may simply be hampered by production techniques with miniature microwave integrated circuit (MMIC) or other technology.
- Soviet researchers are placing increased importance on getting the most out of the current satellite system technology base without having to resort to costly modernization of their Earth terminal equipment. Instead, they are concentrating on developing more efficient multiple-access techniques and incorporating them into new baseband equipment that can be interfaced easily with current Earth terminal equipment, at a minimum cost.
- The larger antennas intended for some spaceborne platforms will enable Soviet researchers to field a capable mobile satellite communications system (they have already tried a primitive system, although no technical information on such a system was identified in the Soviet published literature) and provide increased channel capacity for existing Earth terminals. The larger antennas will also provide the Soviet Union with the capability to field a very-small-aperture terminal (VSAT) system,

although the lack of communications networking capability and computer equipment may hinder deployment of such a system.

- There is on-going research in automating design techniques for electron beam devices such as power amplifiers. This effort is focused on computer-aided design (CAD) and computer-aided manufacturing (CAM) techniques.

B. CHARACTERISTICS OF TYPICAL SOVIET EARTH TERMINALS

Tables VI.1-VI.3¹ provide a sampling of Soviet television receive only (TVRO) antennas, experimental K_u-band terminals, and Intersputnik Earth terminal characteristics. The listed characteristics indicate conservative implementation of well-established technology. For example, all antennas but one are conventional dish-types, and the smallest diameter receive-only antenna has a 2.5-meter diameter.

<p style="text-align: center;">Table VI.1 SOVIET TV RECEIVE-ONLY ANTENNA CHARACTERISTICS</p>			
Characteristic	Ekran-M	Moskva	Moskva-Globalnaya
Frequency	714-754 MHz	3.675 GHz	3.675 GHz
Polarization	Circular	Circular	Circular
Antenna type	"Wave duct"	Parabolic	Parabolic
Antenna diameter (m)	3.6 x 4.8	2.5	4.0
Antenna noise temperature	80°K (with 32-element array)	80°K	55°K
Gain-to-noise temperature (dB/K)	6	14	20.5
Gain (dBi)	30	37.5	41.7
Satellite	Ekran	Gorizont	Gorizont

¹ Varbanskiy, 1989; Kuznetsov et al., 1983; Gassanov et al., 1989; Dobromyslov and Saplov, 1985; Kantor et al., 1986.

Table VI.2
EXPERIMENTAL K_u-BAND EARTH TERMINALS

Characteristic	Class 1 Terminal	Class 2 Terminal
Antenna type	Parabolic	Parabolic
Antenna diameter	12.0 m	3.0-4.0 m
Antenna gain transmit, receive	60 dBi, 59.3 dBi	48.2 dBi (receive only)
Antenna G/T	32.0 dB/K	23.2 dB/K
System noise temperature	537°K	316°K
Receiver noise temperature	250°K	200°K (parametric amplifier)
Transmit power amplifier	1.5 kW klystron	N/A
Transmit EIRP	89.5 dBW	N/A
Planned deployment location	Soviet Union	Eastern Bloc

Table VI.3
INTERSPUTNIK EARTH TERMINALS

Characteristic	Iraq	Yemen
Antenna type	Parabolic	Parabolic
Antenna diameter	11.0 m	11.0 m
Antenna gain transmit, receive	54.4 dBi, 52.0 dBi	55.5 dBi, 53.0 dBi
Antenna G/T	32.0 dB/K	33.0 dB/K
System noise temperature	100°K	100°K
Receiver noise temperature	< 45°K	< 55°K
Transmit power amplifier	3.0 kW klystron	3.0 kW klystron
Transmit EIRP	~ 87 dBW	~ 88 dBW
Date placed into operation	15 Dec 82	15 Oct 86

C. PROJECTED AREAS OF EARTH TERMINAL RESEARCH

Several areas of satellite Earth terminal technology lend themselves to research and development. In the transmit section of the terminal, efforts to increase the HPA's linearity and DC-to-RF conversion efficiency would be primary research targets. On the transmit side, reduction of filter and multiplexer losses would be a focus.

In the receive section of the terminal, good candidates for research and development include low-loss components between the antenna and the LNA, lower noise levels in down conversion and amplifier units, and increased gain and capture efficiency in receive antennas.

At the system level, research and development would be focused on overcoming propagation impairments, reducing antenna noise temperature, increasing polarization discrimination, and environmental design considerations. Propagation at low-elevation angles and to moving terminals are currently subjects of much interest.

The following subsections examine some areas in which research could be expected. This list is not intended to be all-inclusive, but it will provide an overview of the most likely areas of research.

1. Transmit and Receive Antenna System

The performance of the Earth terminal antenna is characterized by several factors, including gain, noise temperature, and beamwidth. The gain is affected by several variables, including efficiency, sidelobe level, diameter of the dish, and the operating frequency. Of these variables, the efficiency and sidelobe level (and the design tradeoffs between them) of the antenna lend themselves to research and development. Research on improving the efficiency of the antenna would likely focus on elimination of surface anomalies, and finding optimal feed configurations and illumination distributions, reducing cross polarization, and reducing scattering and other losses.

The reduction of the antenna's contribution to overall system noise temperature is an area that could be expected to receive some attention. Most of the noise contribution of the antenna stems from atmospheric or galactic noise sources "seen" by the antenna (normally a function of beamwidth, which carries its own tradeoff of cost and operational factors). Additional noise temperature increases are due to losses between the antenna subsystem and the LNA. Feed losses from the antenna to the LNA normally are associated with the antenna, and they raise the effective antenna noise temperature. Efforts to lower antenna noise contributions would most likely focus on reduction of the feed distance to the LNA, lower loss waveguides, more energy-efficient filters (including dual mode filters), and other passive devices in the feed system. The filter area and multiplexer designs are important to Earth station performance. Using the newest RF filter technology could offer great improvements, for example, elliptic function filters and multi-mode cavities.

2. Low-Noise Amplifiers and Power Amplifiers

Research associated with increased performance of LNAs would encompass either an increase in amplifier DC-to-RF conversion efficiency, more amplifier gain without additional noise, or reduction of the noise contribution of the LNA to overall system noise temperature. There are several ways of improving LNA performance, such as cooling the amplification device (cryogenics) and through the application of field-effect transistor (FET) technology (using a variety of substrate materials).

Research associated with improved performance of power amplifiers would likely focus on increasing efficiency, increasing linearity, and improving the gain/bandwidth response of the amplifier. Linearity is an especially important area. All amplifiers saturate because of energy conservation, but, to the extent that they are linear at little less than maximum inputs, they can be operated closer to the maximum power available, without serious intermodulation noise, than can amplifiers that become nonlinear farther from saturation. Improvement efforts would also concentrate on the heat dissipation properties of the PA, which could lead to a less costly heat exchange system for cooling the unit (and a corresponding decrease in the cost and complexity of the Earth terminal).

3. Control and Monitoring Equipment

The primary reason for control and monitoring equipment is to eliminate station downtime by anticipating trouble and to aid in restoration following an equipment failure. Enhancements to the control and monitoring function include faster microprocessor-controlled switchover to redundant equipment, automated fault isolation (AFI) software/hardware combinations, and built-in test capability (BIT) to monitor equipment failures before they become catastrophic.

All enhancements to control and monitoring equipment are aimed at increasing the station operational availability, or A_0 . This is a measure of the station's on-air time versus its downtime and is a function (from an equipment design perspective) of the mean time to repair a failure (MTTR) and the mean time between terminal failures (MTBFs). From a system perspective, A_0 would encompass other factors.

4. Tracking Systems

The complexity of an Earth terminal's tracking system depends on the satellite's orbit. The faster the satellite's angular position changes with respect to the Earth terminal's position, the more capable the tracking system must be to maintain on-axis pointing. Clearly, a satellite in a low-Earth orbit has a much higher speed relative to a stationary Earth terminal than would the same satellite placed in an orbit farther from the Earth's surface.

The complexity of the tracking system also will vary as a function of the Earth terminal's antenna beamwidth, which is a function of the terminal's operating frequency and the diameter of the antenna. For any antenna, the half-power, or 3-dB beamwidth, is inversely proportional to the diameter of the antenna and the operating frequency of the system. The narrower the beamwidth, the more capable the tracking system must be to enable accurate pointing of the antenna.

5. Terminal Equivalent-Isotropic-Radiated Power and Gain-to-Noise Temperature

Two primary transmission parameters for a satellite Earth terminal are the EIRP and a figure of merit called gain-to-noise temperature (G/T) or the ratio of receive gain to system noise temperature. These two terminal parameters (along with system losses, bandwidth, and modulation parameters) are deterministic of the terminal's communications traffic-carrying capacity. The available signal power in a satellite link (uplink or downlink) is a direct result of the radiated EIRP and the receive system G/T .

The elements of a terminal's EIRP (HPA output power, line loss between antenna and PA, and antenna gain) and G/T (LNA noise figure, losses between LNA and antenna, and noise sources "seen" by the antenna) were described in Sections VI.C.1 and VI.C.2, respectively.

6. Environmental Considerations

There are two important environmental considerations: (1) the wind loading, temperatures, and other ambient conditions at the Earth terminal antenna (which cause antenna pointing errors and performance degradation), and (2) RF propagation factors (such as rain, ice, and snow on the antenna or in the propagation path). Although these latter factors are system-related, there are many areas of research that are closely related to Earth terminal technology.

Two areas are well suited to research and development (although the cost/benefit analysis may not warrant it): (1) radome material and composites, and (2) antenna drive systems. It should be noted that radome losses represent both a signal loss and an increase in antenna temperature, so that loss minimization is an important consideration from a system perspective.

D. DISCUSSION

The Soviet Union has placed increasing importance on the geostationary orbit for satellite communications systems,² which, when combined with its growing heavy launch capabilities, will afford it the opportunity to use still less sophistication in its Earth terminal equipment. By focusing their efforts on satellite and baseband/modulation equipment enhancements, such as larger spacecraft antennas and more efficient coding and modulation, Soviet researchers have shown their intention to focus their research efforts on areas other than Earth terminal technology.

The Soviet literature shows surprisingly little new research into Earth station equipment, with only minor enhancements to existing terminal equipment, and almost no effort or investment in ground terminal equipment. The exception to this trend is the Soviet development of increasingly capable baseband systems (both for multiplexing and modulation of signals) in an effort to obtain more use from existing equipment in the cheapest manner (Banket et al., 1988; Kantor, 1988).

The following subsections describe the findings in each of the areas in Section VI.C and include a discussion of manufacturing techniques that are being developed for Earth terminal technology.

1. Antenna System Research

The only inquiries into antenna technology evident in the Soviet literature are associated with the upgraded Ekran television receive station (the upgraded system is called Ekran-M). This development and subsequent equipment upgrade had two objectives: noise temperature reduction in the antenna system and production of environmentally rugged antennas (Kuznetsov et al., 1983; Varbanskiy, 1989).

² N. L. Johnson, *The Soviet Year in Space 1989*, Colorado Springs, Colorado: Teledyne Brown Engineering, February 1990.

The results of this effort are new antenna feed configurations that shorten the distance between LNA and antenna (by mounting the LNA on the RF plate at the antenna), and a series of new antenna systems for the Ekran-M Earth terminals. The new antennas appear to be more capable of withstanding the effects of severe weather such as snow and ice with little or no degradation in antenna performance characteristics. In addition, these new "wave duct" type antennas (a short helix with a plane reflector) are said to have higher gain and directivity than a conventional helix (the axial ratio was between 0.8 and 0.9) (Kuznetsov et al., 1983).

Noticeably absent from the Soviet published literature is discussion of conformal antenna technology (phased or planar arrays, for example), although such research may well be ongoing within the military sector. Such antenna technology would have applications in, among others, mobile terminals and airborne platforms. Recently (early in 1991), Soviet scientists brought a small, C-band phased-array ground terminal to the United States. This prototype terminal was demonstrated at 9.6 kbps over a Soviet satellite located over the Atlantic ocean. No detailed specifications on this terminal were available.

Soviet researchers are quite knowledgeable about antenna theory (Kantor, 1988), and may be limited in the development of these conformal antennas by their production techniques. The same types of technology in which the Soviet Union has traditionally lagged behind the United States, such as mass production of computer chips and memory devices, have applications in phased array antennas. This is particularly true of the newer MMIC designs, where more dense integration of the antenna elements is the driver and the packaging production techniques the common hindrance.

2. Low-Noise Amplifier and Power Amplifier Research

Soviet research into PAs and LNAs has been minimal and is expected to remain at this level for the near future. Soviet researchers devote more effort to improving satellite system energy efficiency through modulation, coding, and multiple-access techniques rather than to investing larger sums of money into Earth terminal RF technology. The primary reasons are twofold. First, Soviet researchers are discussing mounting large satellite antennas on board future

satellites to diminish the need (and the return on such an investment) for developing higher-power PAs and more sensitive LNAs. Second, they are placing greater emphasis on baseband equipment research in an effort to maximize communications system efficiency rather than on expensive research into Earth terminal technology; this, apparently in response to economic considerations. Specifically, Soviet workers seem to be emphasizing quality instead of quantity, shifting from crude modulation and coding techniques that require more power for the link to more efficient techniques that require lower values of E_b/N_0 (energy-per-bit to noise density ratio) for the same error rate and transmission rate, hence, less power (Banket et al., 1988; Kantor, 1983; Zyuko, 1988).

3. Control and Monitoring Equipment

Research on control and monitoring equipment was not apparent in the Soviet literature. The technology level of current monitoring equipment is evidenced by the new Ekran-M Earth terminal, which is monitored by a system using an 8-bit microprocessor that can monitor only 47 data points (Varbanskiy, 1989). No other information on control and monitoring equipment indicated significant Soviet research effort.

4. Tracking Systems

The increasing Soviet use of the geostationary, rather than elliptical, orbits for communications satellites has diminished the need for research into more advanced tracking schemes than those currently employed (such as simultaneous locking, conical scan, and their derivatives). In particular, Soviet researchers are employing a step-track form of automatic tracking (which has sufficient accuracy for satellites in the geostationary orbit) in the new Ekran-M Earth terminal (Varbanskiy, 1989).

As Soviet researchers continue to expand their use of the geostationary orbit, the benefit derived from additional research into tracking equipment and technology will continue to decline. As stated before, they are emphasizing better use of existing equipment. Current tracking systems for LEO and medium-Earth orbit (MEO) satellites are adequate and suggest that no additional research is warranted.

5. Research to Enhance Equivalent-Isotropic-Radiated Power and Gain-to-Noise Temperature Characteristics

Research into improving Earth terminal EIRP and G/T characteristics is, in part, covered under antenna system research. As stated before, Soviet researchers have been exploring the possibility of placing a large antenna (~ 30 m) in space. Such an antenna would have a significant effect on link transmit power and receive antenna size, cost, and complexity.

Specifically, such an antenna would have the following impact on Soviet satellite communications systems connected to it:

- Less EIRP would be required from the Earth terminal (uplink) for the same carrier-to-noise (C/N) ratio, since the antenna would have greater gain than a smaller antenna.
- Less powerful satellite transponders would be required to achieve the same downlink power.
- Smaller receive terminal antennas and less capable LNAs could be used without suffering link degradation.
- Since beamwidth is a function of antenna diameter, such an antenna would have an extremely narrow beamwidth. This is especially good in military applications for both jamming of hostile ground-based antennas and for anti-jam measures to protect satellites from being jammed.

Soviet heavy launch capabilities afford other possibilities in addition to large antennas, such as satellites with powerful transponders and multiply-redundant components. Such a satellite could be placed into orbit with sufficient fuel to last for many years (fuel is normally the limiting factor in a satellite's mission life) and, with the redundancy, it could remain in operation for a long time.

Another possibility is that a wide beamwidth in conjunction with a powerful transponder lends itself well to mobile satellite communications and wide-area coverage. With more powerful transponders on the satellite, sufficient power could be used on the downlink to enable simple receivers to be used (this is particularly true over the Soviet land mass, where interference with terrestrial facilities is not yet a great concern).

6. Environmental Considerations

The Soviet Union is conducting research on environmental protection for Earth terminal antennas (Kuznetsov et al., 1983; Varbanskiy, 1989). This research is discussed in Section VI.D.1 (the new Ekran-M terminal antennas). No other research into environmental factors is evident in the published Soviet literature.

7. Other Considerations Involving Earth Terminals

There is some Soviet research in the area of manufacturing processes, particularly in the production of electron beam devices such as traveling wave tubes. Most of this effort is on automation of design and production techniques in an attempt to enhance quality and increase efficiency.

Table VI.4 lists key Soviet researchers and facilities involved in Earth terminal research.

<p style="text-align: center;">Table VI.4 KEY SOVIET RESEARCHERS AND FACILITIES— EARTH TERMINAL RESEARCH</p>

<p style="text-align: center;">Electrical Engineering Institute imeni Popov, Odessa</p>
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<p style="text-align: center;">A. S. Popov R. A. Lachashvili L. V. Traube L. Ya. Kantor V. D. Kuznetsov (deceased)</p>
--

<p style="text-align: center;">Other Facilities</p>
--

<p style="text-align: center;">"Radio" Scientific Research Institute "Radio" Scientific Production Organization Interkosmos</p>

E. PROJECTIONS FOR THE FUTURE

Soviet researchers are expected to continue to develop their baseband processing capabilities to better use their current technology and existing equipment. They can be expected to continue minor improvement efforts on their Earth terminal RF equipment, especially in the area of production and/or design automation. Neither of these areas has any particular military or commercial impact, but both have the ability to reduce the economic resources dedicated to communications within the Soviet Union.

The most significant impact on Soviet satellite Earth terminal technology will occur when and if the Soviet Union employs a relatively large spaceborne antenna. Milestones to look for include testing of large-diameter parabolic dishes for space-based platforms and continued testing or deployment of a new heavy launch vehicle.

Potential military applications of a narrow beam antenna of the size discussed in Section VI.D would have a significant effect on Soviet military satellite communications and electronic warfare capabilities.

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CHAPTER VI: EARTH TERMINAL RESEARCH

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CHAPTER VII

ANALOG-TO-DIGITAL CONVERSION, STORAGE, AND IMAGE PROCESSING

A. SUMMARY

This chapter examines issues concerning various components that make up non-communications onboard processing systems. Chapter IV also treats onboard processing, but concentrates on communications payloads. As previously shown, the Soviets can easily support 128-Mbps transmissions from space to ground, and up to 36 Mbps via a relay satellite. An attempt is made in this chapter to assess Soviet capabilities in analog-to-digital converters, image processors, and storage, to determine if one or more of these technologies represent a limitation to the Soviet Union in fulfilling stated satellite remote sensing missions. For example, the communications link is the limitation in transmitting 128 Mbps from a Radioastron mission, but onboard storage is the limitation in low-altitude imagery systems such as Almaz.

While several searches of the Soviet literature were made, little useful information was found on these onboard technologies. Thus, other open-source information was used as the basis of this investigation. The Soviet Union appears to be both logic rate limited and onboard storage limited. Both limitations can be easily removed if the Soviet Union can import these technologies from the West or from Japan. If, in fact, the Soviet technology base is logic rate limited as suspected, advanced compression algorithms may not be within Soviet technological capabilities.

B. ONBOARD PROCESSING

A generic onboard processing system, shown in Figure VII.1, consists of a sensor (or sensors), an analog-to-digital (A/D) converter, a processing subsystem, storage, and transmission. The processor itself may require a modest amount of storage, for example, part or all of a video frame. The sensors could be radar, visible, or infrared imagers.

Figure VII.1
Generic Onboard Processing System

The processor and storage may not be required, depending upon the nature of the mission. Transmissions can be accomplished from a spacecraft to a ground station or via a relay satellite to a ground station.

Analog-to-digital converters are fundamental to image processing. A/D converters represent the essential "front end" of image processors. The Soviet literature is filled with articles on A/D conversion techniques. Soviet researchers are very familiar with standard pulse code modulators (PCMs), delta modulators, adaptive differential PCMs, transform coding, linear prediction coders (LPCs), code excited LPCs, and residual excited LPCs. They understand standard compression algorithms, and there is evidence that, on the Resurs-O program, they have developed a compression algorithm for side-looking radars (SLRs) with compression ratios of 75:1.¹ However, it is not known how much degradation is incurred at this relatively high compression ratio.

Soviet scientists have developed PCM A/D converters with 16-bit-per-sample resolution (signal to quantizing noise of 96 decibels). These high dynamic range A/Ds, however, operate at very low sampling rates. The Soviet work appears to be logic speed limited to around 40 megahertz (MHz). For the most part, the Soviets are satisfied with 7- or 8-bit PCM A/D converters for most sensor applications, and therefore we expect their sampling rates to be on the order of 5 megasamples/second for a single 8-bit quantizer. Parallel quantizers could be used to achieve higher sampling rates. Figure VII.2 shows US data covering

¹ *Interavia Space Directory 1990-91*, p. 436-437.

unclassified PCM A/D converters and the estimate of Soviet 8-bit A/D performance.

Figure VII.2
Typical US Analog-to-Digital Converter Performance
and Estimated Soviet A/D Performance for Sensor Applications

- $\left(\frac{S}{N}\right)_Q = \text{signal to quantizing noise} = K \times 2^{2n}$

K = 1 for uniformly distributed input
 = 3/2 for sine wave input
 $\approx 1/4$ for Gaussian input
 n = # bits/sample

- $\left(\frac{S}{N}\right)_Q \approx 6n \text{ dB}$ for uniformly distributed input

(Example: video signal requires 48 dB $\left(\frac{S}{N}\right)_Q$ for high fidelity $\therefore n = 8$)

- In the presence of binary errors, the total $\left(\frac{S}{N}\right)_{\text{out}}$ consists of two terms:

$$\left(\frac{S}{N}\right)_{\text{out}} = \frac{1}{\left(\frac{N}{S}\right)_Q + \frac{4P(1-P)}{(1-2P)^2}}, \quad P = \text{probability of error}$$

Quantizing Binary Errors

$$\left(\frac{S}{N}\right)_{\text{error}} \approx \frac{1}{4P}, \quad \therefore \text{when } n = 8, \text{ for } P \text{ small } P \text{ should be } \leq 10^{-6} \text{ to make noise due to errors negligible}$$

- 8-bit PCM is a standard for a digital video TV channel which requires a nominal 48 db $\left(\frac{S}{N}\right)$ for optimal viewing.

The processing portion of the generic onboard system shown in Figure VII.1 can be considered a special-purpose computer capable of redundancy removal or compression. As stated previously, Soviet researchers are well aware of basic compression algorithms and have developed algorithms with compression ratios up to 75:1. If Soviet clock rates are limited to 40 MHz, as is suspected, this is the rate at which the special-purpose computer can operate for the purpose of compression. Clearly, the processor could be operated at lower speeds if parallel processing is employed. Certain compression algorithms are pipeline or serial processors, while others can be implemented with lower speed parallel processors.

A number of compression algorithms discussed in the Western and Japanese literature have been implemented in hardware. These algorithms falls into two categories:

- Lossless algorithms
 - bit plane coding
 - run length coding
 - Huffman encoding
- Lossy algorithms
 - predictive coding
 - transform coding
 - block truncation
 - vector quantization (VQ)
 - sub-band coding
 - fractal compression
 - wavelets

The Soviet literature did not reveal work in VQ, sub-band coding, fractals, or wavelets. While Soviet researchers appear to understand conventional compression algorithms, they are lagging behind the West in VQ, sub-band, fractals, and wavelets.

Soviet researchers have access to the latest worldwide compression algorithm standard, which is a version of transform coding, discrete cosine transform (DCT). The DCT can provide compression ratios of 16:1, and recent Western implementations have reached 32:1 without significant degradation in image quality. A 1-percent RMS error or loss is the value at which an image begins to degrade, as perceived by the human eye. Most algorithms that provide higher compression ratios, for example, $\geq 16:1$, are computationally intense and often

require microprocessor implementations that operate in the hundreds of mega operations per second (Mops).

A number of US companies and institutions are working on compression algorithms such as transform, VQ, fractals, wavelets, sub-band, and hybrid scheme. Compression ratios of 16:1 to 40:1 are being achieved as a result of the microprocessor technologies from the West. If the Soviet Union is 10 years behind the West and Japan in solid-state devices, as is suspected, then its ability to implement onboard compression algorithms could be severely limited. Table VII.1 compares the current Soviet state of the art in microprocessors with that in the West.

<p style="text-align: center;">Table VII.1 COMPARISON OF SOVIET/WESTERN MICROPROCESSORS</p>		
	Soviet Union	United States
No. of elements per chip	$\approx 2 \times 10^4$	$\approx 10^6$
No. of elements for dynamic random access memory (DRAM)	$\approx 10^5$	$\approx 4 \times 10^6$
Mega operations per second (Mops)	$\approx .1$	≈ 10
Mops per watt	$\approx .5$	≈ 10

C. ONBOARD STORAGE

Film remains the preferred Soviet storage medium for onboard recording of images, with space-to-ground retrieval via deorbited film packages. However, the French have provided the Soviets with a solid-state memory with a capacity of 150 Mbits, but a record/payback rate of 600 kilobits per second (kbps).² The French equipment capacity can be upgraded to 512 Mbits at 600-kbps transmission

² *Interavia Space Directory 1990-91*, p. 515.

<p style="text-align: center;">Table VII.2 ODETIC INC.'s SPACEBORNE TAPE RECORDER SYSTEMS</p>											
	Model										
	5000 PDMS	5000EC ERS-1	5000EC New	B500EC New	6000EC JERS-1	6000EC Landsat-6	9000 New	9500 New	10,000 New	10,500 New	
Tape width (mm)	6.35	6.35	12.7	12.7	25.4	25.4	25.4	25.4	50.8	50.8	
Record rates (Mbps)	0.98/0.781 /1.455	1.093	1 - 100	10 - 300	60	85	3 - 300	3 - 300	10 - 1,000	12 - 1,200	
Playback rates (Mbps)	2.93	15	100	150/300	60	85	150	150/300	600	1,000	
Capacity (Gb)	1.76	6.5	45	105	72	75	250	750	1,000	1,500	
Record times (min)	300/38/20	335/6.7	750/7.5	174/5.8	20	15	1,400/14	4,100/41	16.7	25	
Packing density (kb/cm)	7.3	15	17	27.6	9	9.8	16	27.6	18.6	28	
Record power (W)	19/21/23	65/70	114/117	144/154	110	110	166/170	166/170	318	334	
Playback power (W)	42	115	178/182	235/239	200	200	259	255/259	702	737	
Mass (kg)	10.4	25.0	28.1	33.3	72.6	72.6	72.6	85.3	181	181	
Size (cm) - Transport unit - Electronics unit	23x35 x18	33x38x23 28x34x19	33x38x30 28x34x28	33x38x34 28x34x36	51x51x33 30x51x38	51x51x53 30x51x38	51x51x53 30x51x38	55x55x38 30x51x38	84x69x76	84x69x76	
Availability (months)	24	34	34	34	30	30	36	36	48	48	

Source: *Interavia Space Directory 1990-91*, p. 517

rates. The Soviet spaceborne synthetic aperture radar (Almaz) is said to have an onboard tape recorder with a comparable capacity.³

In contrast to this modest onboard storage capability, the United States has developed high-capacity/rapid readout bought tape systems and solid-state storage. Fairchild Space has a solid-state memory with a 2-gigabyte capacity and readout speeds to 140 megabits per second (Mbps). Odetic Inc. and Lockheed Electronic have developed tape recorders that span a wide range of capacities and rates. These are summarized in Table VII.2. The Soviet capability in onboard storage is expected to remain modest, unless storage devices are obtained from the West and/or Japan.

D. POSSIBLE SOVIET REQUIREMENTS FOR STORAGE AND TRANSMISSION OF REMOTE SENSING DATA

Remote sensing satellites can (depending upon the sensors) generate data at very high rates. Whether this automatically translates into an equivalent requirement for data transmission depends upon the mission concept and the nature of the onboard processing and storage. To illustrate the nature of the tradeoffs involved, we will consider three selected (and idealized) examples:

- A low-Earth-orbit (LEO) satellite collects imagery (visible, IR, or radar) and stores this data in order or transmits it directly to a ground station. This scenario demands large storage and significant processing but provides high-speed communications between the satellite and ground station because of the satellite's proximity to the ground station. Suppose the image is from the visible region and requires medium resolution 2,000 × 2,000 pixels with 12-bit quantization. An image requires 48 Mbits; however, with a DCT compression of 16:1, the image requires 3 Mbits.

The number of images that can be stored on the satellite is:

³ Space Commerce Corp., *Almaz Buyer's Guide* (undated).

$$\text{No. images stored} = \frac{\text{storage capacity}}{3 \text{ Mbit/image}}.$$

The number of images that ultimately can be sent to one ground station in view of this low-Earth orbit satellite is approximately

$$\text{No. images sent to 1 ground station} = \frac{\text{transmission rate (Mbit/sec)}}{3 \text{ Mbit/image}} \times 360 \text{ sec.}^4$$

If the transmission rate is 1 Mbps, then 120 compressed medium-resolution images can be sent to the ground station in view. If the storage is limited, then a modest data rate (1 Mbps) is more than sufficient to accomplish this mention. To date, a solid-state storage of 150 Mbits, which could store 50 compressed images—less than half the hypothetical satellite communication capacity of this example—is attributed to the Soviet Union.

- A LEO remote sensing satellite employs a relay satellite to convey data back to a remote ground station. The onboard processing system is similar to the previous example, with two exceptions: (1) the presence of the relay satellite can reduce the capacity requirements placed on the storage mechanism, and (2) the utilization of the relay satellite generally serves to reduce the data rate that can be transmitted from the LEO through the relay to the remote ground station. As shown in Chapter IV, the current Soviet relay satellite rates should be somewhere between 12 and 36 Mbps, limited by power, apertures, and frequency. On the other hand, the existence of the relay can increase the period of transmissions to the remote station via the relay.
- A highly elliptical orbit (Molniya or higher) is employed, and information is not stored but transmitted to the ground with minimal processing. In general, this scenario provides long viewing times and high through-puts, since the Earth station receiving antenna can be made large. Under this scenario, the Soviet Union will likely be able to trans-

⁴ 360 seconds is taken as a representative viewing time for one ground station.

mit high-speed data directly to the ground with low storage and processing requirements on the satellite.

The first of the above examples is analogous to Almaz as currently operated, where the data acquisition per pass is limited to the 150 second storage capabilities of the onboard tape recorder, while the last example is analogous to Radioastron, where data storage is unnecessary and thus the available data transmission rate is limiting.

E. PROJECTIONS FOR THE FUTURE

The Soviet Union does not appear to have strong programs for developing the complex, high-speed digital signal processors needed for onboard image compression or modern mass storage devices. Therefore, it will likely attempt to acquire these technologies from the West or Japan. Principal technologies of high Soviet interest could be advanced image processors and gigabyte storage with high data rate retrieval, for example, on the order of 128 Mbps.

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APPENDIX A

SOVIET NATIONAL SATELLITE COMMUNICATIONS SYSTEM

As discussed in Chapter IV of this report, the Soviet Union is fully competent in conventional "bent-pipe" communications payloads and has the capability to design and build its own payloads. This is evident from a description of the Soviet national satellite communications system given by Kantor and Timofeyev in the following segment regarding the Soviet national and Intersputnik systems:¹

The USSR's National Satellite Communications System

The USSR began creating the first national transmission communications system in the world in 1965, with the establishment of communications and exchange of television programs between Moscow and Vladivostok through the Molniya artificial Earth satellite. A network consisting of 20 Orbita stations (receive only) that were initially intended to distribute television programs was put into operation in 1967. There are now approximately 100 such stations with antennas 12 m in diameter. However, it is the Moskva and Ekran systems that now distribute the main (first) USSR Central Television program, with the Orbita system now being used to distribute the second Central Television program along five broadcast belts and, first and foremost, to create a communications network. For this purpose, a number of Orbita stations are now equipped with transmitting devices, multistation access equipment, and channel derivation equipment. Both frequency and time access are used (with Gruppa and MDVU-40 equipment, respectively). In all cases, communications signals are transmitted after having been converted into digital form.

The Molniya, Raduga, Gorizont, and Luch artificial Earth satellites are used in the USSR's national satellite communications network. The Molniya-3 artificial Earth satellite has three groups (transponders) that are used to transmit television programs and for telephone communications. This artificial Earth satellite has been established in a high-synchronous elliptical orbit.

The Raduga geostationary artificial Earth satellite has a group that is used to distribute television programs and several communications groups. The Gorizont geostationary artificial Earth satellite has six groups in the 6/4-GHz range. In several artificial Earth satellites of this type there may be a fixed communications group belonging to the Volna system, which operates in the ranges from 1.5 to 1.6 GHz. One of the groups in the 6/4-GHz range has a high power (40 W is fed to the antenna) and a reduced beam (5° x 5°) and is used to create the Moskva television distribution network. Other groups in this range may operate with antennas having a main beam loop with the widths 17° x 17° (the global zone), 6° x 12° (a zone inside the territory of the USSR), and 9° x 18° (a hemisphere zone which is convenient for communications between countries participating in the Intersputnik system). The USSR's geostationary artificial Earth satellites are registered as multiple access with frequency separation under the name Statsionar.

¹ Chapter 2 in L. V. Kantor and V. V. Timofeyev, *Satellite Communications and the Problem of the Geostationary Orbit*, Moscow: Radio i svyaz, 1988.

They are located at a number of points along the geostationary orbit (11° and 14° Longitude W, and 53°, 80°, 85°, 90°, and 140° Longitude E). In one group of a Gorizont artificial Earth satellite with a 6° x 12° (or 9° x 18°) antenna, it is possible to reach a transmission speed of 40 Mbit/s (with time division multiple access and MDVU-40 equipment). Depending on the analog-to-digital conversion method used, this makes it possible to transmit 480 to 960 simplex telephone channels (in groups of 8, 12, or 60 channels). Duplex telephone systems and audio broadcast program distribution systems (Orbita-RV) may be mixed in one group.

Luch satellites operating in the 11/14 GHz-band are used in the USSR's national communications system as well as in the experimental system created under the Interkosmos program.

Small receiving stations belonging to the Moskva system (antenna diameter, 2.5 m) operating in the fixed satellite service range of 4/6 GHz through a special, higher-power group of the Gorizont artificial Earth satellite are widely used to distribute television and audio broadcasts and newspaper band images.

The Ekran system, which has specialized high-power artificial Earth satellites (200 W is fed to the antenna) located at a point 99° Longitude E (registered as Statsionar-T) has been extensively developed in the USSR for television broadcast. The down link operates at a frequency of 714 MHz, which was allocated for radio broadcast satellite services. The frequency 754 MHz has also been used since 1987.

Using a geostationary artificial Earth satellite, the low-frequency range, and a high-power transmitter and directional antenna on the artificial Earth satellite made it possible to use simple and inexpensive ground stations with a transistor input amplifier and "wave channel" in the system. The Ekran system services the territory of Siberia and several adjacent regions.

Because of the flux density restrictions existing in this band, it may not be used in other parts of the USSR.

The Intersputnik International System

The system was created in 1971, and in 1987 it contained 20 ground stations with antennas 12 m in diameter operating in the following countries: Bulgaria, Hungary, the GDR, Poland, the USSR (two stations), the CSSR, Afghanistan, Vietnam (two stations), Laos, Kampuchea, Algiers, Mongolia, Nicaragua, Cuba, the People's Democratic Republic of Yemen, Syria, Iraq, and the United States. All of the aforementioned countries (with the exception of Algiers, Syria, Iraq, and the United States) together with Romania and the Korean Democratic People's Republic are members of the Intersputnik organization. New ground stations are being created in the Korean Democratic People's Republic and the CSSR. Between 1984 and 1987, the stations in a number of countries underwent major redesign. In accordance with the organization's bylaws, ground stations are the property of the participating countries. The space segment (groups or parts of groups) is leased to a Gorizont-type satellite of the Soviet Union (registered as Statsionar-4 and Statsionar-5, located respectively at 14° Longitude W and 53° Longitude E). The exchange of television programs and telephone communications occurs in the system on a wide scale.

Frequency modulation with a peak deviation frequency of ± 13 MHz for the video and accompanying sound transmission (on a carrier frequency of 7.5 MHz with a deviation of ± 150 kHz) are used when transmitting television programs. This is carried in a 36-MHz bandwidth transponder.

Telephone messages in large groups (60 or 12 channels each) are transmitted by using time division multistation access in digital form (MDVU-40 equipment). Gradient equipment with frequency access and transmission of each channel on a separate carrier in analog form with frequency modulation (single carrier per channel) are used when the number of channels is small. The introduction of a new generation of equipment having multistation access with frequency separation and transmission of each channel on a separate carrier with the transmission of signals in digital form, i.e., Interchat equipment, began in 1986.

Ground stations belonging to the Intersputnik system should have a Q-factor (G/T) of no less than 31 dB/K, an operating frequency range between 6025 to 6225 MHz for transmission and 3700 to 3900 MHz for reception, and an equivalent isotropically-radiated power of 84.6 dBW for transmission in a television mode and 51.8 dBW in a telephone mode based on the method of transmission of each channel on a separate carrier.

The level of the sidelobes of the ground station antennas at angles of $1^\circ < \theta < 48^\circ$ conforms to the current CCIR recommendations of $(29 \text{ to } 25) \log \theta$.

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APPENDIX B

ABOUT THE AUTHORS

J. Neil Birch (*Panel Chairman*). Dr. Birch is President of Birch Associates, Inc., which specializes in the field of Communications, Command, Control, and Intelligence (C³I). He received a BS in Electrical Engineering from North Carolina State University (1958), and an MS (1961) and a PhD (1965) in Electrical Engineering from the Catholic University of America. Previous positions held by Dr. Birch have included: Principal Director and Deputy Assistant Secretary of Defense, Office of the Assistant Secretary of Defense (C³I); Advisor to the Director, Telecommunications and Command and Control Systems (DTACCS), Office of the Secretary of Defense, and Assistant Director for Systems and Advanced Technology; Chief Scientist, US Navy Command, Control and Communications (C³) Programs, Office of the Chief of Naval Operations; Director of Advanced Systems Analysis Office, Magnavox Company; Division Chief, National Security Agency; Staff Engineer, Western Electric Company. He has experience in the following areas: World-Wide Military Command and Control (C²) System: European C²; Tactical C² Systems and TRI-TAC; Defense Communication System; Military and Domestic Systems; Digital Voice Coding; Secure and Privacy Communications: Spread Spectrum and Error Control Coding; Navigation Aids; UF and Meteor Modeling; Remote Monitoring; Telecommunications Technology Forecasting; Maritime, Aeronautical, and Meteorological Satellite Systems; and Intelligence and Intelligence-Related Programs. Dr. Birch is the author of numerous publications and is active on a number of Department of Defense (DoD) panels. He is also a member of the Institute of Electrical and Electronics Engineers (IEEE), Sigma Xi, the National Space Institute, the Armed Forces Communications Electronics Association, and an Elected Fellow of IEEE.

S. Joseph Campanella. Dr. Campanella is Vice President and Chief Scientist of COMSAT Laboratories. He received a BS in Electrical Engineering (*magna cum laude*) from the Catholic University of America (1950), an MSEE from the University of Maryland (1956), and a PhD in Electrical Engineering from the Catholic University of America (1965). Prior to assuming his current position, Dr. Campanella was the Executive Director of the Communications Technology Division at COMSAT Laboratories, and was the leading architect of the 120-Mbps TDMA (time division multiple access) system now used operationally in the INTELSAT system. He has contributed to a number of important technical developments in data communications, digital speech interpolation, TV image processing, DAMA (demand-assigned multiple access) techniques, digital modulation and demodulation and echo cancellation for improving the quality of long propagation delay satellite circuits. Because of his extensive experience in advanced satellite communications concepts involving on-board baseband signal processing and channel switching as related to ACTS (advanced communications technology satellite) and other NASA programs and in end-to-end integration of satellite communications networks, especially in the time division multiple access area, he has been asked to participate in panels providing guidance to NASA on the space station information system and on space station applications to science programs such as EOS (Earth Observation Satellite) and Space Telescope and commercial satellite communications systems. Dr. Campanella's recent work has been devoted to scientific and engineering efforts directed toward the development of new, economical communications satellites that can meet the needs of future satellite telecommunications services for military and domestic applications; study of an on-board digital processor that will simultaneously demultiplex and demodulate multiple carriers of different bandwidths and modulation formats that can be reprogrammed for different carrier configurations; and study of advanced communications satellite network architectures that will permit the adaptive on-board restructuring of uplink and downlink traffic by use of a destination directed on-board switching device. He also serves as a technical advisor to the ACTS program for COMSAT and is a member of the Data Panel of the Space Station Users Group at the Goddard Space Flight Center. Dr. Campanella has

written numerous technical papers on advanced satellite communications concepts; is the author of chapters on TDMA and digital channel multiplication in recent books on digital satellite communications; and, most recently, is the author of several national/international conference papers dealing with the cost of delivery of future satellite telecommunications services using advanced communications satellite network architectures and their harmonious integration with fiber optic terrestrial networks. He also holds a number of patents in the area of satellite communications. He is a Fellow of IEEE and the American Academy for the Advancement of Science (AAAS), an Associate Fellow of the American Institute of Aeronautics and Astronautics (AIAA), and a member of Sigma Xi and Phi Eta Sigma. He is the recipient of the 1990 IEEE Award in International Communications.

Gary D. Gordon. Dr. Gordon is an independent consultant. He received a BS in Physics from Wesleyan University (1950), and an MS in Physics (1951) and a PhD (1954) from Harvard University. Since 1984, he has consulted on satellite operations, satellite orbits, satellite reliability studies, a satellite cost model study, and has done some numerical analysis. He has recently written a book with Walter Morgan, *Communications Satellite Handbook* (John Wiley & Sons, Inc.). From 1969 through 1983, Dr. Gordon was Senior Staff Scientist in the Spacecraft Laboratory at COMSAT Laboratories. He consulted with members of the technical staff on a variety of activities and worked on spacecraft positioning and orientation, mechanical bearings, system reliability analysis, satellite in-orbit servicing, and computer programming. From 1958 to 1968, he was with RCA (now GE), where he contributed to the thermal design of the first weather satellite (TIROS), and was responsible for the thermal design of the RELAY communications satellite. He was also active in an RCA education program teaching RCA managers modern physics, semiconductor devices, and computers. He has written technical papers on electric propulsion, the geodetic use of satellites, spacecraft thermal design, and a proposed 30-kW solar array. Prior to 1958, he spent two years at the US Army Biological Warfare Laboratories in Frederick, Maryland, and two years at Operations Research, Inc., in Silver Spring. Dr. Gordon is a member of AIAA, Sigma Xi, and Phi Beta Kappa. He was a member of the first *COMSAT Technical Review* editorial board, and has served on various computer committees. He has taught courses in spacecraft technology, satellite orbits, satellite reliability, spacecraft thermal design, FORTRAN programming, and Speakeasy programming.

David R. McElroy, Jr. Dr. McElroy is Leader of the SATCOM System Engineering Group at the Massachusetts Institute of Technology's (MIT) Lincoln Laboratory. He received a BSEE, an MSEE, and a PhD from the Georgia Institute of Technology. After graduation in 1970, he served as an officer in the US Army, where he directed an autonomous communications networking research and development project at the Army Electronics Command, and later led a civil engineering section in Vietnam. He received a Commander's Commendation Award and the Bronze Star Decoration from these respective assignments. Since joining Lincoln Laboratory as a Staff Member in 1972, he has been involved in the analysis and synthesis of communications and radar systems, as well as with the design, in-flight testing, and technology transfer activities associated with the Laboratory's Advanced Satellite Communications Program. In 1976, 1978, and 1980, respectively, Dr. McElroy became the Assistant Leader, Associate Leader, and Leader of the Laboratory's SATCOM System Engineering Group. Concurrent with these managerial responsibilities, he has served as the Program Manager for Lincoln's support to DoD's MILSTAR Program (1981-1984), the USAF Advanced Satellite Communications (1977-1984) and Survivable Satellite (1976-1980) Programs, and the Navy's Submarine Communications Program (1976-1978). From 1984 to 1987, he led the group that developed the communications signal processing, command/telemetry, and power systems for the FLTSAT EHF Payloads (FEPs). He currently leads a group that is developing advanced system concepts and associated technologies for future satellite communications systems with improved performance. Dr. McElroy has prepared more than 40 technical reports, journal articles, and meeting speeches. In addition, he has been active in IEEE and AIAA, where he has served as Chairman of the AIAA Technical Committee on Communications Systems (1981-1983) and as the Deputy Direc-

tor for Information Systems on the AIAA Technical Activities Committee (1984-1987). In 1984, he received the AIAA Shuttle Flag Award for his contributions to the Institute's communications systems activities. He has also been a member of the NASA Space Systems and Technology Advisory Committee and has served as Chairman of the Communications Panels for the USAF Space Division/AIAA Space Systems and Technology Workshops II (1982), III (1984), and V (1989).

Wilbur L. Pritchard. Mr. Pritchard is President of W. L. Pritchard & Co., Inc., a consulting firm which provides engineering services in telecommunications, with a strong specialty in satellite communications. He received a BSEE from the City College of New York (1943), and pursued graduate studies at MIT (1948-52). He has over 45 years of experience in technical design, systems engineering, management, and international negotiations. He has been associated with the design and development of satellites since the inception of the communications satellite era. He has been responsible for leadership and administration in large corporations such as Communications Satellite Corporation, and has directed and participated in difficult technical programs covering the entire range of satellite engineering. Mr. Pritchard is a Professorial Lecturer at George Washington University (since 1988) and an Adjunct Professor of Electrical Engineering at Polytechnic University of New York (since 1985). He has published more than 40 papers, and has contributed to three books and co-authored two (most notably, *Satellite Communication Systems Engineering*, W. L. Pritchard and J. A. Sciulli, Prentice-Hall, Inc., 1986). He also holds more than a dozen patents in microwave applications. He is a Fellow of IEEE, AIAA, and the British Interplanetary Society, a Senior Member of the American Astronautical Society, a Charter Member and past Chairman of the Board of the Society of Satellite Professionals (SSPI), and holds honors from a number of professional and government organizations.

Reinhard Stamminger. Mr. Stamminger is President of Future Systems International Corporation, a company that currently concentrates on the implementation of satellite-based telephone services for developing countries. He received his BSEE (equivalent) from the Technical Institute (TGM), Vienna, in 1955—with a major in electronics and telecommunications. He is a member of the order of Engineers of Quebec, Canada. Mr. Stamminger has 35 years of experience in the design of telecommunications equipment and systems with emphasis on satellite transmission. Jointly, with Orion Network Systems, he formed PhoneSat International Corporation, a company that will provide satellite telephone services for East European and other developing countries. He has worked on the design of a large number of communications satellite systems for national and international applications. As Director of Systems Engineering at the Communications Satellite Corporation, Mr. Stamminger had responsibility for the design of the INTELSAT-IV and INTELSAT-IV-A systems and the definition of the INTELSAT-V system. In a consulting capacity, he worked on the systems design for the first Brazilian domestic system, on the design of the WESTAR/TDRSS communications systems and on the design of the Southern Pacific/GTE Spacenet System. Mr. Stamminger also supported a range of NASA activities in the development of the 20/30-GHz program that led to the ACTS system.

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APPENDIX C

GLOSSARY OF ABBREVIATIONS, ACRONYMS, AND SELECTED TERMS

AA	antenna array
AAAS	American Association for the Advancement of Science
AC	alternating current
ACTS	advanced communications technology satellite
A/D	analog to digital
AF	audio frequency
AIAA	American Institute of Aeronautics and Astronautics
AJ	anti-jam
Almaz	("Diamond") Soviet remote sensing (radar) satellite
AN SSSR	<i>Akademiya nauk SSSR</i> (USSR Academy of Sciences)
APT	altitude pointing telemetry
Arkus	Soviet geostationary communications satellite (equipped with inclination control) that will succeed Gorizont in 1991
AS USSR	USSR Academy of Sciences
A-U	All-Union
bps	bits per second (also b/s)
BPSK	binary phase shift key(ing)
C	celsius
CCD	charge-coupled device
CCIR	International Consultative Committee for Radio (<i>Comité Consultatif Internationale de Radio</i>)
CEMA	see CMEA
CFE	channel-forming equipment
C ³ I	Communications, Command, Control, and Intelligence
cm	centimeter
CMEA .	Council for Mutual Economic Assistance: a multilateral economic alliance headquartered in Moscow; members include Bulgaria, Cuba, Czechoslovakia, Hungary, Mongolia, Poland, Romania, the Soviet Union, Vietnam (and, formerly, the German Democratic Republic)
C/N	carrier-to-noise (ratio)
COCOM	Coordinating Committee: a multilateral body for establishing/ implementing controls for technology transfer to the Soviet Union and Eastern Europe based upon national security considerations; includes all of the NATO countries (except Iceland) and Japan
CPFSK	continuous phase frequency shift keying
CR	compression ratio

DAMA	demand-assigned multiple access
dB	decibel
dB/K	decibels per Kelvin
dBi	decibels above isotropic
dBW	decibels above 1 watt
DC-to-RF	direct current to radio frequency
DCT	direct cosine transform
DMSK	differential minimum shift keying
E	East (longitude)
Eb/No	energy-per-bit to noise-density ratio
EHF	extra high frequency (30-300 GHz)
EIRP	equivalent-isotropic-radiated power
Ekran	("screen") Soviet geostationary communications satellite for direct television broadcast
Ekspress	("express") Soviet geostationary communications satellite (equipped with inclination control) that will succeed Gorizont in 1992
EORSAT	electronic ocean reconnaissance satellite
EOS	Earth Observation Satellite (NASA satellite)
ESA	European Space Agency
EUTELSAT	European Telecommunications Satellite
FDMA	frequency division multiple access
FEC	forward error control
FEP	FLTSAT EHF Package
FET	field-effect transistor
FFT	fast Fourier transform
FLTSAT	Fleet Satellite Communications System (or its satellites)
FM	frequency modulation
Gals	("tack") Soviet geostationary communications satellite (transponder)
Gbps	gigabits per second (also Gb/s)
GE	General Electric
GEO	geostationary Earth orbit
GHz	gigahertz

Glavkosmos	Main Administration for the Development and Use of Space Technology for the National Economy and Scientific Research (<i>Glavnoye upravleniye po sozdaniyu i ispol'zovaniyu kosmicheskoy tekhniki dlya narodnogo khozyaystva i nauchnogo issledovaniya</i>): administers Soviet civilian international space programs; responsible for satellite design, construction, launching, information collecting, and for remote sensing
Glonass	Global Orbiting Navigation Satellite System (Soviet Union)
GOMS	Geostationary Orbit Meteorological Satellite (system)
Gorizont	("horizon") Soviet geostationary communications satellite
Granat	("garneť") Soviet-launched satellite for X-ray and gamma-ray observations
GS	ground station
GSFC	Goddard Space Flight Center
G/T	gain-to-noise temperature; G/T is the spacecraft antenna gain divided by the spacecraft receiver noise temperature expressed in dB/°K, and is a measure of the satellite's receiving capability in terms of signal and noise levels
GW	gigawatt
HPA	high-power amplifier
ICSC	Interior Communications Satellite Committee
IEEE	Institute of Electrical and Electronic Engineers
IMPATT	impact ionization avalanche transit time (microwave amplifier device)
INTELSAT	International Telecommunications Satellite Organization
Intersputnik	Soviet International Organization of Space Communications, headquartered in Moscow; international consortium to rival the INTELSAT system in providing communications services
IR	infrared
ISDN	Integrated Services Digital Network
Iskra	("spark") Soviet radio satellite
ITU	International Telecommunications Union (headquartered in Geneva, Switzerland)
K	Kelvin
kb	kilobit
kg	kilogram
K-K	space-to-space
km	kilometer
Kosmos	("space") Soviet satellite/launch vehicle
kbps	kilobits per second (also kb/s)
kW	kilowatt

LEO	low-Earth orbit
LNA	low-noise amplifier
LPC	linear prediction coder
LSI	large-scale integration
LSI/VLSI	large-scale integration/very large-scale integration
Luch	("ray/beam") Soviet geostationary communications satellite
m	meter
Mbits	megabits
Mbps	megabits/bytes per second (also Mb/s)
MEO	medium-Earth orbit
MESFET	metal semiconductor field-effect transistor
MHz	megahertz
MIPS	million instructions per second
MIT	Massachusetts Institute of Technology
mm	millimeter
MMD	mean mission duration
MMIC	miniature/monolithic microwave integrated circuit
mN	milli-Newton
Molniya	("lightning") Soviet communications satellites with highly elliptical orbits
Mops	mega operations per second
Moskva	("Moscow") Soviet satellite communications system; in conjunction with network of microwave links and land lines, enables both First and Second Programs of Central Television to be relayed to vast area
MSK	minimum shift keying
N	North (latitude)
NASA	(US) National Aeronautics and Space Administration
nmi	nautical mile
NPO	<i>nauchno-proizvodstvennoye ob'yedineniye</i> (scientific production association)
Okean	("ocean") Soviet all-weather radar oceanographic satellite
OPSK	octal phase shift key(ing)
Orbita	("orbit") Soviet complex of ground stations used in conjunction with dedicated communications satellites; each can receive television transmissions relayed through geostationary and Molniya satellites, with further relay to surrounding areas; can also receive/transmit telephone, telegraph, facsimile, and weather data via the Molniya satellites

PA	power amplifier
PCM	pulse code modulation
PCM/PSK	pulse code modulation/phase shift keying
PFD	power flux density
PSK	phase shift key(ing)
QAM	quadruphase amplitude modulation
QPSK	quaternary phase shift key(ing)
R&D	research and development
Raduga	("rainbow") Soviet communications satellite
RF	radio frequency
RMS	root mean square
RORSAT	radar ocean reconnaissance satellite
RS	("radio sputnik") Soviet radio satellite
RTG	radioisotope thermoelectric generator
S	South (latitude)
SAR	synthetic aperture radar
SAW	surface acoustic wave
SCPC	single channel per carrier
SDRN	Satellite Data Relay Network
SHF	super-high frequency (3-30 GHz)
SLR	side-looking radar
SSPI	Society of Satellite Professionals
SSSR	<i>Soyuz sovetskikh sotsialisticheskikh respublik</i> (USSR)
t	tonne/metric ton
TACSAT	tactical satellite
TDMA	time division multiple access
TDRSS	Tracking and Data Relay Satellite System
TVRO	television receive only
TWT	traveling wave tube
TWTA	traveling wave tube amplifier
UHF	ultra-high frequency (300-3,000 MHz)
USAF	US Air Force
VLSI	very-large-scale integration
Volna	("wave") Soviet communications satellite (transponder)

VQ	vector quantization
VSAT	very-small-aperture Earth terminal
W	watt; West (longitude)
W/g	watt/gram
whr	watt-hour
whr/kg	watt-hour/kilogram
W/kg	watt/kilogram

APPENDIX D

SOVIET JOURNALS CITED IN TEXT/REFERENCES

For readers not familiar with the Soviet technical literature, a key to the abbreviated titles of the Soviet serial literature cited in this report is provided below. The titles of the English-language translations used are listed in **bold print** and the original Russian-language titles are in *italics*. When a given Soviet technical journal is published in more than one commercial translation, the English title for the same Soviet source may vary with the publisher. If translations have been made privately (for example, government agency translations), the titles may also vary. Frequently, English titles are not literal translations of the original Russian. Therefore, knowledge of the Russian title of a journal may be necessary to identify reference materials.

Abbreviation	English Translation Title/ <i>Original Russian Title</i>
Cosmic Res.	Cosmic Research <i>Kosmicheskiye issledovaniya</i>
Electr. Eng.	Electrical Engineering <i>Izvestiya vysshikh uchebnykh zavedeniy (VUZ), Elektromekhanika</i>
Instrum. Exp. Tech.	Instruments & Experimental Techniques <i>Pribory i tekhnika eksperimenta</i>
Moscow Univ. Math. Bull.	Moscow University Mathematics Bulletin <i>Vestnik Moskovskogo universiteta, Seriya 1, Matematika, mekhanika</i>
Radioelectron. Commun. Syst.	Radioelectronics & Communication Systems <i>Izvestiya vysshikh uchebnykh zavedeniy (VUZ), Radioelektronika</i>
Radio Eng. Electron. Phys.	Radio Engineering & Electronic Physics <i>Radiotekhnika i elektronika</i>
Radiophys. Quantum Electron.	Radiophysics & Quantum Electronics <i>Izvestiya vysshikh uchebnykh zavedeniy (VUZ), Radiofizika</i>
Sov. Aeronaut.	Soviet Aeronautics <i>Izvestiya vysshikh uchebnykh zavedeniy (VUZ), Aviatsionnaya tekhnika</i>
Sov. J. Commun. Technol. Electron.	Soviet Journal of Communications Technology & Electronics <i>Radiotekhnika i elektronika</i> (formerly/until 1985 Radio Engineering & Electronic Physics)
Sov. Phys.-Dokl.	Soviet Physics-Doklady <i>Doklady Akademii nauk SSSR</i>

Telecomm. Radio Eng.

Telecommunications & Radio Engineering
Elektrosvyaz/Radiotekhnika
(selected translations)

APPENDIX E

FASAC REPORT TITLES

(* asterisk before title indicates report is classified)

(completed)

FY-82/83	* Soviet High-Pressure Physics Research Soviet High-Strength Structural Materials Research Soviet Applied Discrete Mathematics Research * Soviet Fast-Reaction Chemistry Research
FY-84	Soviet Physical Oceanography Research Soviet Computer Science Research Soviet Applied Mathematics Research: Mathematical Theory of Systems, Control, and Statistical Signal Processing Selected Soviet Microelectronics Research Topics * Soviet Macroelectronics (Pulsed Power) Research
FY-85	FASAC Integration Report: Selected Aspects of Soviet Applied Science Soviet Research on Robotics and Related Research on Artificial Intelligence Soviet Applied Mathematics Research: Electromagnetic Scattering * Soviet Low-Energy (Tunable) Lasers Research Soviet Heterogeneous Catalysis Research Soviet Science and Technology Education Soviet Space Science Research FASAC Special Report: Effects of Soviet Education Reform on the Military Soviet Tribology Research Japanese Applied Mathematics Research: Electromagnetic Scattering Soviet Spacecraft Engineering Research Soviet Exoatmospheric Neutral Particle Beam Research Soviet Combustion Research Soviet Remote Sensing Research and Technology Soviet Dynamic Fracture Mechanics Research
FY-86/89	Soviet Magnetic Confinement Fusion Research Recent Soviet Microelectronics Research on III-V Compound Semiconductors Soviet Ionospheric Modification Research Soviet High-Power Radio Frequency Research Free-World Microelectronic Manufacturing Equipment FASAC Integration Report II: Soviet Science as Viewed by Western Scientists Chinese Microelectronics

(completed/cont'd.)

FY-86/89 Japanese Structural Ceramics Research and Development
System Software for Soviet Computers
Soviet Image Pattern Recognition Research
West European Magnetic Confinement Fusion Research
Japanese Magnetic Confinement Fusion Research
* Soviet Research in Low-Observable Materials
FASAC Special Study: Comparative Assessment of World Research Efforts on
Magnetic Confinement Fusion
FASAC Special Study: Defense Dependence on Foreign High Technology
Soviet and East European Research Related to Molecular Electronics
Soviet Atmospheric Acoustics Research
Soviet Phase-Conjugation Research
* FASAC Special Study: Soviet Low Observable/Counter Low Observable Efforts:
People and Places
Soviet Oceanographic Synthetic Aperture Radar (SAR) Research
Soviet Optical Processing Research
FASAC Integration Report III: The Soviet Applied Information Sciences in Time
of Change
Soviet Precision Timekeeping Research and Technology
Soviet Satellite Communications Science and Technology

(in production)

FY-86/89 West European Nuclear Power Generation Research and Development
* Radiation Cone Research
FASAC Special Study: Non-US Artificial Neural Network Research

FY-90/91 Soviet Chemical Propellant Research and Development
Soviet Optoelectronics Research
Soviet Parallel Processing Research
Soviet Nonlinear Dynamics Research
Foreign Research Relevant to Countering Stealth Vehicles
Soviet Research in Penetration Mechanics
Soviet and Free World Bandpass Radome Research and Development
FASAC Special Study: Non-US Artificial Neural Network Research
Soviet Macroelectronics (Pulsed Power) Research

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