CR-72637

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NASA CR-72637

TELEVISION BROADCAST SATELLITE STUDY

RESEARCH AND TECHNOLOGY IMPLICATIONS REPORT

by

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Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

January 26, 1970

CONTRACT NAS 3-9707

NASA Lewis Research Center
Cleveland, Ohio

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1. INTRODUCTION

This report presents the research and technology implications identified in the Television Broadcast Satellite Study conducted by TRW Systems Group under contract NAS 3-9707 with NASA Lewis Research Center.

The objectives of this study were to define and examine in detail the technological and cost factors affecting the feasibility of Television Broadcast Satellites in the 1975-1980 time period. The results of these investigations are presented in Document NASA CR-72510, Final Report of the Television Broadcast Satellite Study.

The investigations of technological and cost aspects were centered about, but not restricted to, three spacecraft configurations. The major characteristics of these configurations are presented in Tables 1 and 2.

The 12kw; 0.9 GHz configuration, with an estimated recurring cost of 21.6 million dollars per flight article, provides one channel to an area of $1.0 \cdot 10^6$ square statute miles ($2.5 \cdot 10^6$ km^2). The vision transmission is amplitude-modulated with vestigial sideband (AM/VSB). Viewers using a 6 ft (1.8 m) parabolic antenna and an adapter, with an estimated total retail price of $80 in addition to the regular television set, can receive color or monochrome broadcasts of fine quality (TASO Grade 2) in rural environment, or fine-to-passable quality (TASO Grade 2 to 3) in urban environment with high level of manmade noise.

The 4 kw, 2.5 GHz configuration, with an estimated recurring cost of 13.8 million dollars per flight article, provides seven frequency-modulated TV channels, each to an area of $1.0 \cdot 10^6$ square statute miles ($2.5 \cdot 10^6$ km^2). For reception of color or monochrome television of fine quality (TASO Grade 2), viewers need special equipment at an estimated retail price of $160 in addition to the regular television set.

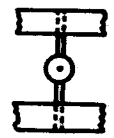
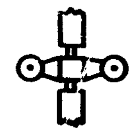
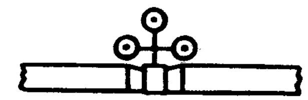
The 8 kw, 12 GHz configuration, with an estimated recurring cost of 17.8 million dollars per flight article, can provide one frequency-modulated TV channel to two areas, each $0.25 \cdot 10^6$ square statute miles ($0.63 \cdot 10^6$ km^2). Reception of color or monochrome television of fine quality (TASO Grade 2) under bad weather conditions (rain and fog) in a temperate climate requires special user equipment with an estimated total retail price of $240.

Table 1 Satellite Summary Descriptions

	Configuration		0.9 GHz	2.5 GHz	12.0 GHz
Communications	Modulation		AM/VSB	FM	FM
	Number of Video Channels		1	7	1-2(3)
	RF Output Power/Channel	(kw)	13.2(1)	0.30	5.0
Antenna	Number of Transmitter Antennas		1	2	2
	Transmitter Antenna Diameter (ft)		30	10	4.5
	Receiver Antenna Diameter (ft)		2.5		
Configuration	Body Orientation		Earth-center	Earth-center	Sun
DC Power	Array Power	(kw)	12.2	4.13	8.0
	Communications Power Load	(kw)	10.8	3.36	7.0
High Temperature Dissipation	RF Output Amplifier(s) at maximum output	(kw)	2.5	1.26(2)	2.0
	RF Output Amplifier(s) at minimum output	(kw)	1.8	N/A	N/A
Low Temperature Dissipation	Transmitter(s)	(kw)	0.10	0.20(2)	0.1
	Pwr Conditioner for Xmitter(s)	(kw)	0.87	0.38(2)	0.58
	Other Power Subsystem Units	(kw)	0.14	0.14	0.14

(1) Sync. peak power
(2) Total for all transmitters (including redundancy)
(3) Dependent on user installation and climate conditions

Table 2. Television Broadcast Satellite

Item			
Configuration	Earth Oriented "H" Configuration	Earth Oriented "I" Configuration	Sun-Oriented Body Configuration
Power - Frequency	12.4 kw - 900 MHz	4 kw - 2500 MHz	8 kw - 12,000 MHz
Solar Array	Roll Out 1950 Sq ft^2 (181 m^2) Axis parallel to orbit plane	Fold Out 630 Sq ft (58 m^2) Axis normal to orbit plane	Fold Out 1280 Sq ft^2 (119 m^2) Axis parallel to orbit plane
Body Orientation	Earth Center	Earth Center	Sun
Rotary Joint	Slip Ring	Slip Ring	RF Rotary Joint
Antenna Arrangement	(1) 30 ft (9.15 m) diameter transmitter antenna dish (1) 2-1/2 diameter (0.8 m) receive antenna	(2) 9 ft (2.8 m) diameter antenna dish transmitter	(3) 4-1/2 (1.4 m) diameter antenna
Satellite Weight	3600 lb (1630 kg)	1600 lb (7730 kg)	2200 lb (1000 hg)
Booster	Titan IIIC modified 7 Seg/Std Stg I/Stretch Transtage	SLV IIIC/Centaur/Burner II	TIIIC 5 Seg/Stg I/Transtage
Propulsion ● Attitude control ● Initial positioning ● Station keeping	Cold gas (N_2) Hydrazine Colloid system	Cold gas (N_2) Hydrazine Colloid system	Cold gas (N_2) Hydrazine Colloid system

The discussions of the technology aspects of the spacecraft and of the special user equipment for reception of broadcast satellite transmissions, presented in the Final Report, are applicable to a wide variety of possible spacecraft configurations.

The Television Broadcast Satellite Study resulted also in parametric cost data versus performance for the spacecraft, the special user equipment, and the master station. In addition, potential audiences are identified and the benefits of television broadcasting by spacecraft are discussed for application to education.

2. RESEARCH AND TECHNOLOGY IMPLICATIONS

2.1 COMMUNICATIONS SUBSYSTEM

Except for high-power transmitter output amplifiers, communication subsystems for television broadcast satellites can be built today with the technology used in communication satellites presently in operation.

The present state-of-the-art in spaceborne rf power amplifiers reaches to output powers of a few hundred watts. For output power levels above, say, 0.5 kilowatt, further development is necessary. Technological advances are absolutely required to achieve a 5-year life with adequate reliability (>0.7) and to provide adequate and reliable cooling commensurate with the 5-year life requirement. Improved transmitter efficiency relaxes the cooling requirements, to a theoretical limit, and is therefore as important for feasibility as cooling capacity.

Enhancement of efficiency further relaxes requirements on the design of large solar arrays, and when developed, yields savings in satellite costs or earth receiver costs.

Recent studies of multi-kilowatt rf amplifiers resulted in analytical designs. In these studies, primary emphasis was on achieving high overall efficiency. All these designs feature multi-stage depressed collectors as the method yielding the largest efficiency improvement. Heat-pipe configurations for cooling were presented in all studies, while life was approached primarily from the viewpoint of cathode design and loading. Amplitude linearity for AM/VSB and phase linearity (group delay) was examined in varying degree.

Clearly, experimental verification of efficiency, thermal design, life and linearity is required. Experiments in simulated environment, and considerable hardware development is required before operational spaceborne amplifiers with output levels above 1 kw can be produced.

Development of light-weight rf circuit components (including diplexers and filters) capable of handling high average power (up to 10 kw) in space environment is required. The critical issues are multipaction and cooling.

Local oscillators with adequate frequency stability $(2 \cdot 10^6)$ are within the present state-of-the-art. The use of advance solid-state devices such as avalanche diodes, Gunn and LSA mode devices are not strictly necessary for feasibility, but will most likely offer simpler and more reliable circuits. In view of the present rapid development of these devices, separate activity for the Television Broadcast Satellite Mission is not recommended.

Overall subsystem development will be required for specific designs, with emphasis on linearity and stability of high-gain amplification, isolation between transmitter and receiver, and thermal isolation.

2.2 ANTENNAS

2.2.1 Reflector Antennas

A fundamental requirement on antennas for television broadcast satellites will be concentration of the total radiated power on a limited area. At the lowest frequency of interest, 0.9 GHz, this requirement dictates the use of satellite antennas as large as about 30 ft (9 m) to cover an area with a diameter of 1000 miles, or even 60 ft for a 500 mile coverage.

The critical issues are weight, deployment reliability, and the geometric accuracy of the surface when subjected to dynamic and thermal distortion in space environment. The surface accuracy requirements are set primarily by the acceptable limits on sidelobe levels and pointing accuracy.

Substantial efforts have been spent on the design of unfurlable antennas with wire-mesh surfaces. To date, space flight experience has not been obtained with antennas larger than 10 feet (3 m).

Further full-scale model development and testing is required to obtain the level of confidence in reliability and performance, required to commit a 30 ft deployable antenna to a space mission.

Feed configurations for large reflector antenna capable of handling multi-kilowatt power levels are not state-of-the-art. Development is required to achieve illumination patterns for low sidelobe levels, and power handling capability up to 10 kilowatts average. The critical issues of the latter objective are multipaction and thermal control.

Shroud limitations on spacecraft dimensions will in general prohibit the use of more than one large deployable reflector antenna. Multiple beam transmission by reflector antenna can then be achieved only with a multiple-feed arrangement. The main problems with this approach are geometric conflicts at the feed and the feasibility of low-level sidelobes. Coma caused by off-axis location of feed radiation centers and coupling between feeds have adverse effects on the sidelobe level. An array-type of feed is a potential solution. Further development is required if multiple-beam transmission by a single reflector is an actual requirement. Any decisions on such development should be made first after consideration of the potential capabilities of phased arrays.

2.2.2 Phased Arrays

The potential advantages of phased arrays are:

- Beam pointing without attitude disturbance torques.
- More freedom in aperture distribution design than possible with reflector antenna feeds permits achievement of lower sidelobe levels.
- Multiple-beam capability without adverse effect on sidelobe level.
- With active arrays, distributed power dissipation facilitates thermal control.

Phased arrays fed by a single transmitter compare unfavorably with reflector antennas because of the large weight of a phased corporate feed network with full rf output power capability and the heavy power losses in such network. Only active arrays, with final amplification at each element (or small group of elements) are potentially competitive, and then only at the lower frequencies, 0.9 GHz and 2.5 GHz.

Active arrays for the present application is not within the present state-of-the-art. With the rapid development of solid-state devices for microwave power generation, it appears possible that active arrays at 0.9 GHz and 2.5 GHz become competitive for missions in the 1975-1980 time period. This would require development in the following areas:

- Design of elements such as a strain energy deployable reflector with a complementary pair feed, or a strain energy deployable helix.

- Power capability and efficiency of transmit modules.

- Deployment of array with feed network.

- For multiple-beam capability: feed network development.

2.2.3 RF Rotary Joints

The critical issues of rf rotary joint design for the present application are multipaction and thermal control. Apparently, there is not sufficient evidence of feasibility from tests in simulated space environment. RF rotary joints for power levels above 1 kw can therefore not yet be considered state-of-the-art.

In the present application, the use of rf rotary joints is warranted only when the spacecraft body is sun-oriented. Since earth-oriented antennas are indicated for both downlink and uplink, the rf rotary joint must handle both the high transmitter output power and the considerably lower received rf signal power. Thus at least two channels are required, and isolation between these channels is a severe design criterion.

Additional development and testing of rf rotary joints is required before a spacecraft with sun-oriented body can be built with rf output level over 1 kilowatt.

2.3 ELECTRICAL POWER

Silicon solar cell arrays are within the present state-of-the-art. Development is required for adaption to bus voltages of at least 100 volt.

In the areas of array deployment, structural design and orientation considerable development efforts is in progress. The Pegasus mission has shown the feasibility of deployment. The structural development required for the television broadcast mission will be primarily adaption of existing technology to the particular spacecraft dynamics and attitude control performance.

DC sliprings are within the present state-of-the-art. Additional development is required for adaption to a bus voltage of at least 100 volts. Consideration should also be given to possible outgassing problems, bush redundancy requirements, and the risk of cold welding associated with high current density at contacts with low slip velocity.

Efficient conditioning of multi-kilowatt power is not within the present state-of-the-art. Additional development is required in the following areas:

- Modular, high-power, multi-kv, self-protecting collector power supplies regulated for input line and load variations.
- Converters for recovery of energy from collectors and feedback to input bus.
- Output filters to supply synchronizing power and provide low output impedance for amplitude modulation induced load variations.
- High power solid-state inverters operating from input voltages 200 to 500 volts for improved conversion efficiency.

2.4 ATTITUDE CONTROL AND STATIONKEEPING

The control system analyses performed in the present study resulted in the recommendation of 3-axis control using colloid engines for attitude control and stationkeeping during normal operational conditions, and hydrazine for trim maneuvers after orbit injection and initial orientation, and for reacquisition maneuvers in case of loss of control. This approach is within the present state-of-the-art, except for 5-year life of colloid engines. Life tests in simulated space environment, are being performed. Further development may be required to achieve 5-year life.

With a transmit antenna beamwidth of 3 degrees, beam pointing to an accuracy of 0.1 degree is required to keep pointing error losses within 0.5 db. With interferometer techniques using sensors mounted on the transmit antenna, control of the sensor mount orientation within $\pm$ 0.1° is feasible with state-of-the-art techniques. However, dynamic and thermal distortion of the transmit antenna causes an unknown offset between the actual beam direction and the sensed direction. This error would be removed if the interferometer signals used the transmit antenna reflector. Development of such system is recommended.

The dynamic interactions of structural flexibility, primarily in large antennas and large solar arrays, with the attitude control require development of accurate models to represent the flexible systems and development of hybrid computer software to examine the dynamic interactions. Several studies are required to clarify various aspects of the interaction simulation which heretofore received only scant attention. These are:

- Development of more realistic non-viscous models for structural damping.
- Investigation of the modal coupling effect through damping.
- Effect of discrete dampers on the motion of a flexible spacecraft
    - Viscous Dampers
    - Impact Dampers
    - Eddy Current Dampers
    - Magnetic Hysteresis Dampers.
- Development of analytical models for description of the characteristics of interconnections of structural members (joint interface, backlash, etc.).
- Study of dynamic isolation of spacecraft components, for example, isolation of a 22 ft boom from the control system of the OGO spacecraft.
- Improved control configurations
    - Type, number and location of sensors which will provide accuracies of better than $\pm$ 0.1 deg.
    - Auxiliary control systems designed to maintain the shape of sensitive spacecraft components (large dish antenna).
    - Improved actuators in control system design.

Hardware development will be required to shape the frequency response of the solar array drive servo system for dynamic isolation of the array from the spacecraft body. Also, active elastic oscillation damping sensors and dampers need to be developed.

2.5 THERMAL CONTROL

Two specific areas need significant development work before a satisfactory thermal control system could be designed. Large, deployable antennas required an integrated thermal structural analysis with a high degree of sophistication. The high heat density sources also present a difficult design problem which has not been encountered in previous spacecraft.

2.5.1 Deployable Antenna Thermal Analysis

The preservation of satisfactory rf performance in large parabolic antennas in space requires that the reflecting surfaces be maintained close to their original geometry during flight. External thermal inputs in space, such as solar heating, tend to produce gradients that may result in distortions of the antenna surfaces. Thus, an essential part of the required analysis is the prediction of the temperature and distortion profiles and resultant antenna performance. This analysis must have a high degree of sophistication since satisfactory thermal vacuum testing of these large antennas is beyond the capabilities of existing environmental simulation facilities.

An integrated thermo/structural analysis procedure is required to determine temperature distributions and distortions. It is clear that this could only be done through computer simulation. The effect of various hole patterns in the antenna must be included. Resultant differential shading of the antenna for various solar inclination angles must be simulated in the computer program. Conduction and radiation interchange between the antenna and support structures must be included. A program capable of describing highly redundant structures must then be integrated with the thermal analysis.

2.5.2 High Density Cooling

Cooling of the rf tube presents a difficult problem because of the high heat densities expected at the source. The density is high enough, in most cases, as to preclude heat removal by radiation. An active system must thus be designed for transfer of heat from the source to a radiator surface of sufficient area for rejection at a suitable temperature. Two systems have been identified in this study; heat pipe system and circulating liquid system.

Considerable development would be required to apply either system. Long lifetime requirements of TV Broadcast Satellite impose severe reliability constraints on the motor-pump combination of any active system. Since the system does not operate during eclipse periods, control of the system to prevent undercooling would be required. The fluid must be capable of withstanding both heat during operation and cold during eclipse. The development of heat pipe system must include both configuration and fluid for high heat transfer density.

2.5.3 Low Density Cooling

The low-density cooling of all power conditioning equipment and low-power, internal equipment is controlled by louvers. This method is within the state-of-the-art. Warping of louvers under sunlit condition may require some application development.

2.6 USER EQUIPMENT

The user equipment consists of a space-oriented antenna and electronic equipment to adapt a regular television receiver to satellite transmission. Development of the adapter is currently being pursued by General Electric under contract with NASA. The results of these efforts should lead to indication of further development requirements.

System cost and performance would benefit from development of low-cost, circularly polarized antennas. Low sidelobes and backlobe are desirable for rejection of manmade noise and earth radiation noise.

3. PRIORITY

<u>First priority</u> should be given to the development objectives required for feasibility of an experimental mission. These include:

- RF output power amplifiers with high efficiency.
- Thermal control of transmitters.
- Power conditioning for transmitters.
- Solar array deployment.
- Dynamic interaction of flexible structures.

<u>Large deployable antennas</u> are <u>necessary</u> for feasibility only for broadcasting at 0.9 GHz.

Items of <u>second priority</u> are those required for feasibility of a 5-year operational mission, and those with potentially significant impact on performance or cost. These items are:

- Antenna feed design for low sidelobes.
- Multiple-beam transmission by single-reflector antenna.
- Active phased arrays.
- RF rotary joints.
- Adapation of solar array technology to bus voltages over 100 volt.
- DC slipring design for bus voltages over 100 volt and 5-year life.
- Colloid engines for 5-year life.
- RF techniques for sensing of true direction of transmit beam.