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An Evaluation of Television Broadcast Satellite Systems

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This paper presents the results of an evaluation of technological and cost factors associated with TV Broadcast Satellite (TVBS) systems which would operate with modified home receivers or special receiving equipment. The costs of the ground and space segments of the system and the effects of variations in technical parameters on these system costs are considered. Transmission at 0.8, 2.5, 8.4, and 12.2 GHz, amplitude and frequency modulation, and ground receiving equipment cost ranges of $0–$150 and $1000–$50,000 are examined. Sample conceptual designs are described for selected requirements utilizing technology estimates of the early 1970's.

Introduction

OF all of the applications of today's space program, the Television Broadcast Satellite (TVBS) has the greatest potential for directly helping the peoples of the world. The purpose of the studies described in this paper is to define total systems which are optimized in terms of specific service needs and projected means of payment. Both the ground and space segments of the systems are examined to assure that the economics could be evaluated in the proper perspective. Since the number of possible specific services is so large, wide ranges of parameters are examined. The services have been grouped into two major categories for this study. Direct service is for use by the general public in the home. For this service the ground investment is restricted to $0–$150. Special service is for special groups viewing at a smaller number of selected centers, and for inputs to terrestrial broadcast stations. Here, the range of ground investment is $1000–$50,000.

Systems Model

The over-all system is synthesized in a computer model. The performance of the ground receiving system is defined and optimized as a function of the ground investment and the number of units assumed to be required (audience). The minimum cost satellite is defined as a function of required radiated power output and area coverage. The orbit is assumed to be geostationary, based on previous studies which show that satellite systems are most effective when used almost continuously.[1] The final portion of the model accounts for integration and amortization factors, and combines the ground and space segment costs in various ways to permit over-all evaluation and comparison with other methods of providing a particular service. The system amortization period was assumed to be 10 yr, based on the probable life of the ground receiving equipments. The satellite life (including launch vehicle reliability) is estimated to be 2 yr. Thus, five satellite-booster systems are required for a 10-yr program. It is probable that steps taken to assure a 2-yr satellite will readily yield a 5-yr satellite; however, the 2-yr amortization is used to maintain conservatism.

The ranges of technical parameters considered and/or the values used for discrete calculations are 1) signal grade: TASO grades 1, 2, 3; CCIR relay quality; 2) frequency/modulation: AM-0.8, 2.5 GHz; FM-0.8, 2.5, 8.4, and 12.2 GHz (chosen to be representative of the ranges 0.47–0.89, 2–3, 8.3–8.5, and 11.7–12.7 GHz, respectively); 3) audience size (number of receivers): 10^4–10^8 direct services; 10–10^5 special services (evaluated in order of magnitude steps); 4) coverage areas (10^6 sq. miles): $\frac{1}{2}$, 1, 3, 10; 5) number of TV channels: 1–6 video/area (up to 3 areas); 1–4 audio/video; 6) largest booster permitted: Titan 3F/Centaur; payload range of 8000–10,800 lb in geostationary orbit.

Receiver Synthesis

The receiver synthesis model defines the maximum performance that can be achieved within a specific ground receiver cost limit. This receiver cost is the installed cost of the antenna, electronics, and interconnection necessary to receive the satellite signal and supply an output capable of driving standard home television receivers or in the case of special services, providing baseband output. Maximum performance results in the minimum Effective Radiated Power (ERP) required from the satellite. The receiver synthesis model operates on the input parameters of picture quality, frequency/modulation, modulation index, number of receivers, and the allowable cost per receiver. Where not defined as an input, the model will select that modulation index resulting in the minimum signal level. In defining the optimum ground configuration, all possible combinations of electronics and antenna alternatives are investigated.

An example of ground antenna models is shown in Fig. 1. A separate model of this form was developed for each frequency. Both fixed and tracking antennas are considered to

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permit a tradeoff of north-south stationkeeping in the satellite vs tracking antennas on the ground. Gain vs cost relationships are shown for production quantities up to 10^5. Costs encompass total installation and include the reflector and feed, mount, installation, and alignment. Antenna and ground electronics cost and performance represented in this model are based on data from a survey on manufacturers. Ground receiving electronics costs have been considerably influenced by the rapid advancements predicted for integrated circuits. Example costs for an X-band FM converter are given in Table 1 for production quantities up to 10^5.

Satellite Synthesis

The satellite synthesis model operates on the required ERP, the number of video and audio channels, and the desired coverage area size to define the combination of satellite subsystems that meets the performance requirements for minimum cost. In addition, the model accepts inputs to adjust the ERP requirement (ΔERP) to account for the location of the coverage area and ionospheric and atmospheric transmission losses. Satellite subsystems are represented in the model in terms of engineering cost, manufacturing cost, and weight as a function of subsystem performance. The antenna, transmitter, power, attitude control, thermal control, structures, and propulsion subsystems are considered as variables in the model; other subsystems (e.g., tracking, telemetry, and control) are treated as fixed points. The model considers antenna pointing accuracy ranges from 0.02° to 2°. For each accuracy assumed, the required antenna beamwidth is defined for the required coverage area. This defines the antenna gain, and, therefore, the rf power output required to supply the defined ERP. The satellite power requirement is then a function of the transmitter d.c. to rf efficiency. Structural weight is defined, based on the subsystem weights and the structural stiffness required by the attitude control system natural frequency limitations. The minimum size booster capable of launching the satellite into geostationary orbit is selected and the subsystem data are combined to produce the over-all satellite cost. All possible combinations of control accuracy and other subsystem options are iterated, and the combination meeting the input requirements for minimum cost is selected. An example of subsystem cost and performance data utilized is shown in Fig. 2. This example shows the data defining cost and weight of X- and S-band satellite FM transmitters as a function of the output power. (Performance and cost factors for all models are projections of the technology for the early 1970's.)

Cost Summation and Model Outputs

Outputs of the ground and space segment models are combined in the systems cost model to derive the system costs, which include management, supporting system investment, operational costs, and amortization. All reasonable combinations of the technical parameters are considered and the resultant costs in various forms are defined. The systems costs generated by this model are 1) Satellite Engineering Development Cost (SEDC): design, development, and test for spacecraft and design and development of support equipment (i.e., AGE and manufacturing tooling); 2) Satellite Annual Operation Cost (SAOC): $\frac{1}{2}$ (satellite manufacture and launch vehicle), plus support subsystem operation (i.e., uplink, telemetry, and control operation), plus $\frac{1}{10}$ satellite ground investment (i.e., uplink, AGE, and manufacturing tooling); 3) Total Satellite Cost (TSC): SEDC, plus 2 SAOC (this covers the initial 2 yr of satellite operation); 4) Total System Implementation Cost (TSI): SEDC, plus 10 SAOC, plus unit ground receiving costs times number of receivers. (This covers the initial 10 yr of system operation.)

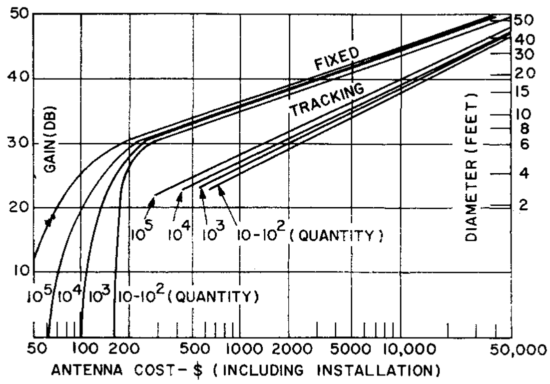


Fig. 1 Receiving antenna performance/cost relationships (2.5 GHz).

One output of the model is plots of the four systems costs as a function of the costs per ground receiving site. An example of the curves for SAOC and TSI at 8.4 GHz is shown in Fig. 3 for a special service system providing 18 channels of CCIR relay quality. Curves are given for 10, 3, 1, and $\frac{1}{2}$ million sq. mile coverage areas. The figure shows that as the allowable ground receiving equipment cost increases, the power required from the satellite, and therefore the satellite cost, decreases. An optimum ground equipment cost can, therefore, be identified for minimum total system implementation cost. Generally, for a small audience, the total cost is satellite dominated; for a large audience the ground costs dominate. The specific optimum, however, is a function of area coverage and desired picture grade.

Figure 3a presents cost relationships for an audience of 100 receivers. Increasing the investment in ground receiving equipment beyond a relatively low value (approximately \$5000–\$10,000 for this case) results in no significant decrease in satellite or total system cost. Figure 3b shows the same system requirements for an audience of 1000 receivers. In this case, increased ground investment beyond approximately \$5000 would increase the TSI for large coverage areas. These examples are representative of the trend identified for all per-

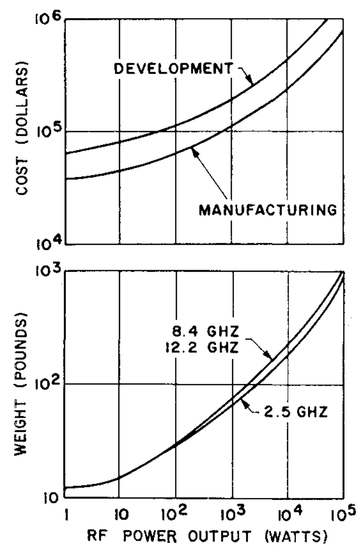


Fig. 2 Transmitter performance/cost relationships (FM-linear beam).

Table 1 FM converter cost (8.4 and 12.2 GHz)

Configuration: preamplifier?	NF,[a] db	Unit cost (\$) quantity 10	10^2	10^3	10^4	10^4
No	9.0	73	44	28	18	13
Yes	5.2	84	51	32	21	14
Yes	1.9	1,546	903	528	309	183
Yes, cooled	1.0	38,000	22,000	13,000	8,000	4,000

[a] $NF_{(db)} = 10 \log 10 [(290 + T_R)/290]$; T_R = receiver noise temperature, °K.

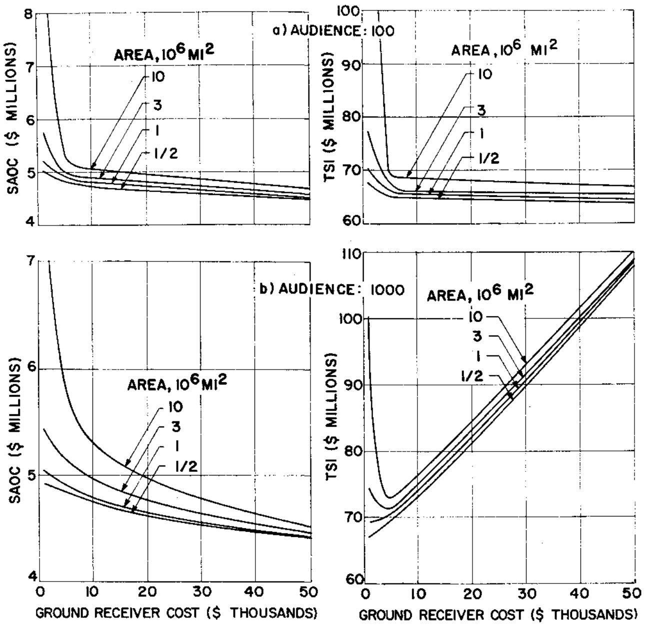


Fig. 3 System cost curves for special service, CCIR relay quality, 18 channels, 8.4 GHZ, and FMFB.

formance requirements in this study; the false economy in using a low-power satellite and a large ground station is clearly shown.

A second output of the model is curves showing the variation of required ERP as a function of the amount of ground receiver dollars (for each of the values of picture grade, frequency, modulation, noise environment, and number of receivers). Figure 4 is an example output for a frequency of 2.5 GHz, AM modulation, an urban noise environment, and 10^6 receiving stations. Note that a picture quality of TASO grade 1 with a ground receiving cost of \$100 requires the satellite to provide an ERP of 85 dbw. The value of ERP relates to an area with its center at the subsatellite point, and would be increased accordingly for other coverage locations and for ionospheric and atmospheric propagation factors.

The third output of the model shows the satellite costs (annual operation, engineering, and total system) as a function of ERP required (see Fig. 5). The figure shows, for example, that for an ERP of 65 dbw over an area of 3 million sq. miles on the ground, the satellite would have an annual operating cost of about \$14 million.

The fourth form of data presentation utilizes the system synthesis model on a single case basis. This provides a complete print-out of all the performance, type, weight, and cost data for the totals and for each of the components of the optimized system. Detailed evaluation of the results or examination of design points between the quantized values in the trade curves is thus permitted. This form can also be used as the design baseline for the next level of design.

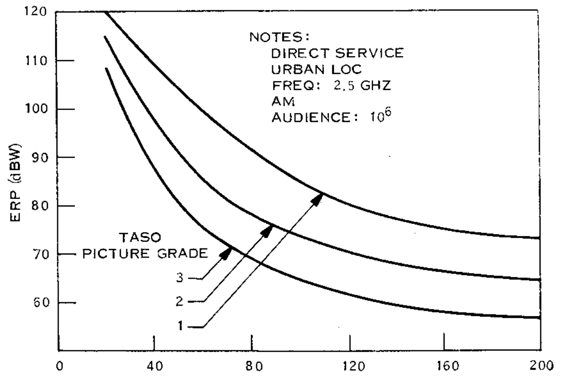


Fig. 4 Signal strength requirements.

Table 2 Potential space TV service

Name	General description
	Special services
ITV	Instructional television for formal classroom use
"Medical" TV	An instructional service for medical or other postgraduate training
TV distribution	To distribute TV signals for retransmission by terrestrial broadcast stations
	Broadcasting services
TV broadcast for the Americas	To broadcast TV signals to the continents of north and south America
RTV	Provide TV service to rural, fringe, and low population density areas
GTV-D/E	General purpose television for developing and emerging nations
CTV	Cultural television for developed areas
Urban TV	To provide TV service to urban areas
UN-TV	Worldwide system of disseminating UN, UNESCO, etc.

Definition of TVBS Services

To obtain results related to specific missions, it was necessary to define potential TVBS services. This was done in conjunction with NASA and a Space Broadcast Advisory Board composed of senior executives and experts of many broadcast-related vocations. Their evaluation of potential services is shown in Table 2.

Example Systems

Three potential TVBS services were selected as representative of the range of technical and service requirements: I. a community/distribution service to India, II. a direct service to Alaska, and III. an instructional service to the U.S. These three were structured to examine in detail the system interfaces and designs.

Case I. Community/Distribution Satellite for India

By providing a simple community receiving system (minimal operation and maintenance requirements), audio-visual presentations can be implemented rapidly by utilization of broadcast satellites. India is a good example of a developing nation, since its population is clustered in villages and spread over a large area. Since this type of service is directed toward nations in which use of the rf spectrum is now minimal, the broadcast service parameters can easily be optimized on a cost-effectiveness basis. A distribution service, at 8.4 GHz, was

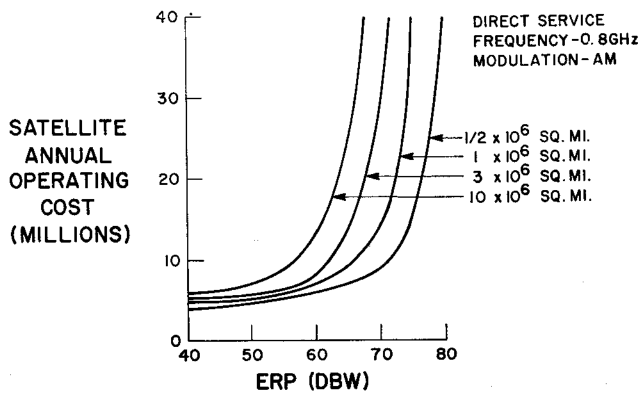


Fig. 5 Satellite performance/cost relationships.

Table 3 Receiver component characteristics for example systems

Component	Description			
	Case I		Case II	Case III
	Community	Distribution		
Antenna				
Type	Helix	Paraboloid	Prime focus paraboloid	Prime focus paraboloid
Size, diam	12 in. × 5 in.	13.9 ft	5.2 ft	8.8 ft
HPBW, deg	49	0.59	16.5	0.64
Gain, db	10	48.4 nom (47.1 net)	19.5 nom (18.9 net)	47.7 nom (46.5 net)
Cost—installed, $	37.00	2045.00	85.00	620.00
Electronics				
Type	Preamp + modul conv	Preamp + freq and modul conv	Preamplifier	Preamp + freq/modul conv (6 channel)
Noise figure, db	3.0	1.9	3.3	1.9
Cost, $	10.50	903	12.50	475.00
Transmission line	30 ft twin lead costing $2.50			

added in this satellite to deliver signals to ground television stations in the major cities.

The community service is the most demanding of the two, and is thus selected as the critical design condition for optimum satellite performance. Minimization of TSI cost is the optimization criteria used, since one entity would be likely to bear the entire cost. Figure 6 shows that TSI cost is minimized at an expenditure of approximately $50 on the ground receiver equipment, operating at UHF with frequency modulation. (Estimates are based on U.S. costs. Adjustments may be needed for other countries to obtain absolute values, but the relationships shown would remain constant.) A description of the selected ground receiver equipment is presented in Table 3 for the two services.

The satellite longitudinal positioning selected was the stable point at 77°E (which is within 2° or 3° of the optimum location for India). The half-power beamwidth (HPBW) coverage provided is shown in Fig. 7, with the beam centered at 79°E, 20°N. To cover the portion of India between East Pakistan and Burma (Assam), the transmitting antenna would have to be of HPBW = 5°; but, the rest of India can be conveniently covered by a HPBW = 4°, as shown. It was decided to provide the basic coverage to the major portion of India and increase ground receiving sensitivity in the Assam region. The cost of the additional ground antenna gain to provide the 4–5 db for the extreme off-axis location in Assam is about $10/antenna. With about 20,000 villages in Assam, the additional increment on the ground system cost would be $200,000. The cost of providing 1.9 db (0.5 kw) additional power on the satellite would be about $1.8 million for a 10-yr period; thus, the trade is much in favor of the selected approach.

Satellite Configuration

The satellite for this service to India employs a sun orbit-normal reference system to fully orient the solar array to the sun, and a cooperative ground beacon for pointing the transmitter to the desired location on the earth. This requires a full 360°/day rotation of the solar array assembly with respect to the antenna/body module, accomplished with low-voltage d.c. slip rings. Seasonal inclination of the solar array to track the sun is accomplished by a $\pm 23\frac{1}{2}°$ motion using a flex harness. The satellite antenna package consists of a deployable 21-ft-diam UHF antenna with a concentric X-band antenna (8.4 GHz) mounted on the back of the prime focus feed. The apogee kick motor used with the Atlas/Agena booster was assumed to be nominal design of the Surveyor type employing a mass fraction of 0.9 and an I_{sp} of 290 sec. The satellite configuration is shown in Fig. 7 with a weight breakdown by subsystem. A cost breakdown of the satellite system and supporting systems is presented in Table 4.

Cost Comparison

The worth of a satellite broadcast system becomes evident when the satellite system is compared to the cost to implement and operate a terrestrial microwave/cable relay link (the alternate approach to providing the TV services). The costs developed here for comparison are based on certain assumptions made to permit modeling; however, the results are felt to be representative of realistic situations. The model assumes UHF stations transmitting at an ERP level of 1000 kw from antennas 1000 ft above ground. The effective radius of coverage of the station is dependent upon the height above ground of the receiving antenna. The received picture quality is a function of the noise figure of the electronics and the gain of the receiving antenna. For these systems, the receiver is assumed to be a standard TV set with no preamplifiers, and the antenna gain requirement is dependent upon distance from the station. Total system cost is a function of two elements: 1) the transmitting station installation and operation and 2) the receiver installations.

Since the receiving antenna installation cost is proportional to the distance from the station (and thereby inversely proportional to the number of transmitting stations and their total cost), there is an operating point for minimum cost dependent upon the number of receivers. In general, the minimum total cost will occur by minimizing the number of transmitters required. This can occur through extension of the coverage radius to a practical maximum by installation of high-gain receiving antennas on towers at the fringe areas. Therefore, the coverage radii were established to be 52

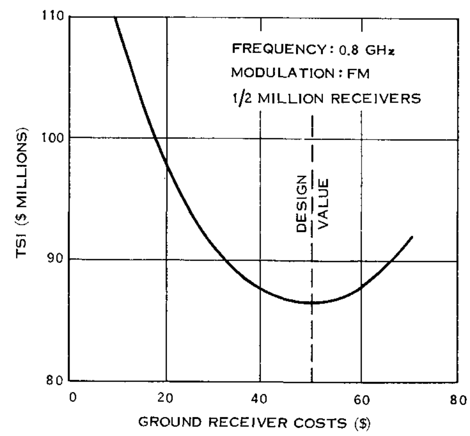
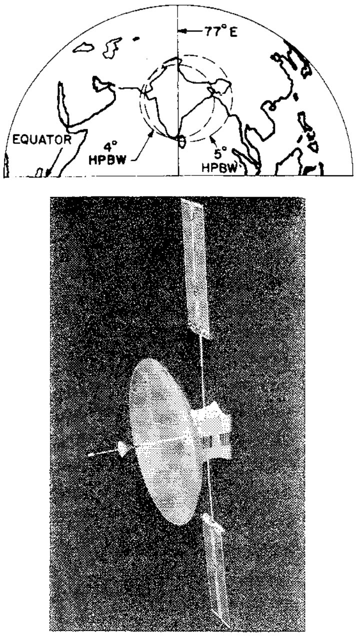


Fig. 6 System implementation costs—community service.



Subsystem	Weight, lb
Power supply	150
Receiver exciter	28
Transmitter	33
Antenna	120
Attitude control	86
Thermal control	43
Structure	137
Propulsion	135
Track, telem., cont.	20
Total	752

Fig. 7 Beam coverage and satellite concept—community service to India.

statute miles for a direct service to a home or community receiver and 55 miles for a special service instructional TV receiver. This is based upon receiving antenna heights of 30 and 50 ft, respectively. In addition to the coverage radius, the second element determining the required number of stations is the desired portion of the area to be covered. The models chosen for comparison in this study provide 85% for home/community coverage and 65% for instructional coverage. These values are considered reasonable for existing similar systems.

To provide the grade 2 picture or better to the 1.1×10^6 sq. miles of India would require 110 transmitting stations spaced 100 miles apart. The initial investment cost would be \$80 million for the microwave links and stations,[2] and \$10 million for receiving antenna installations (based on 260,000 of the 500,000 receivers requiring antenna gains varying from 13 db at 52 miles from the station down to about 2 db at 36 miles). The annual operation cost would be about \$6 million, and the total cost for a 10-yr program would be approximately \$150 million. The comparable 10-yr cost for a community broadcast satellite would be \$87 million based on a \$50 receiver cost for the 500,000 units and \$62 million for the satellite development and operation. Thus, the cost ratio of the terrestrial-to-satellite approach is almost 2:1 in favor of the satellite.

The payload for the distribution service was added to the satellite to accommodate anticipated needs of the major metropolitan areas as they develop their local TV transmitting facilities. The cost of adding this service to the satellite was relatively insignificant, and is included in the foregoing cost data. The additional cost of a ground station required to receive this service is about \$3000 when operating at X band utilizing frequency modulation.

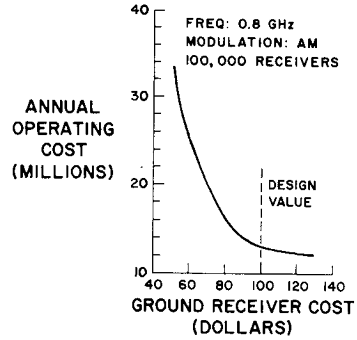


Fig. 8 System operation cost — direct service to Alaska.

Case II. Direct Broadcast to Alaska

This type of service provides general purpose television to sparsely populated remote regions. It should receive ready acceptance by inhabitants with available resources to purchase the needed equipment and provide maintenance. The example target area is Alaska; three channels are provided. The development and installation of this type of satellite system is likely to be borne by the U.S. government, the ground system installation cost borne by the user, and the operation conducted by a broadcasting company. This implies that either the satellite annual operating cost and/or the receiver cost be the governing cost for minimization. For this service, it was decided to restrict operation to the current UHF/AM standards of terrestrial broadcast.

In this case, the cost factor evaluated was the sum of the amortized costs of the ground receiving equipment (using a 10-yr amortization) and the satellite annual operating cost. This sum decreases rapidly with increasing ground receiver cost up to about \$100 (Fig. 8). The ground cost of \$100 was chosen for this system since increases do not significantly reduce the total cost and would tend to make the service less attractive to the user. Ground receiving equipment for this service comprises an outdoor antenna, a preamplifier, and transmission lines. The equipment characteristics are presented in Table 3.

Longitudinal positioning of 135°W for the satellite was selected so that the satellite can receive an uplink from the western U.S. and be able to transmit to any portion of Alaska, excluding the Aleutian chain. A more easterly location would be desirable so the satellite could easily receive uplink transmission from the eastern U.S., but the local time in Alaska precludes this. At 120°W, which would accommodate an eastern U.S. uplink, the satellite eclipse at

Table 4 Example system costs

Cost category:	Cost(millions \$) Development/ engineering			Fabrication or replacement			Annual operation			Investment		
Item / Case:	I	II	III	I	II	III	I	II	III	I	II	III
Satellite system	13.3	20.8	22.0	3.4	9.2	5.9	...	...	...	...	...	...
Launch vehicle	1.0	1.0	1.0	4.2	13.0	4.2	...	...	...	...	...	...
Supporting systems	0.5	0.9	0.6	...	...	...	0.8	0.9	0.8	1.3	1.7	1.4
Ground receivers	...	...	...	...	...	...	...	...	...	25.0	10.0	11.0

	Case I	Case II	Case III
SAOC	$(3.4 + 4.2)/2 + 0.8 + 1.3/10 = 4.7$	12.2	6.0
SEDC	$13.3 + 1.0 + 0.5 = 14.8$	22.7	23.6
TSI	$10 (4.7) + 14.8 + 25.0 = 86.8$	154.7	94.6

equinox would occur at approximately 9:30 PM, local Alaska time. Because 9:30 PM is too early, the satellite was positioned at 135°W to extend cutoff time to 10:30 PM.

The rf radiation pattern for Alaska should be squinted to compensate for the extreme latitude, since a circular beamwidth would give excess spillover in the N-S direction and result in inefficiency. A 3° beamwidth in the E-W direction will adequately cover the region from Ketchikan to the Alaskan peninsula, and, if the beam is yawed, the N-S coverage can be achieved with a 1° beam. Therefore, a 1° × 3° elliptical beam was selected with the resultant coverage shown in Fig. 9 for a 60°N, 145°W beam center location.

Satellite Configuration

Direct service to Alaska would require significant increase in power levels and size from present day satellites. One reason for this is that broadcasting is done with existing standards, using AM modulation. This requires much higher power levels (≈5.5 kw). The other reason is that the restriction to UHF as the carrier frequency causes the squinted narrowbeam antenna to be extremely large (29 ft × 80 ft). The high-power level requires fully oriented solar arrays that rotate about the pitch axis 1 revolution/day with respect to the antenna.

The size, orientation, and rotation requirements impose a serious constraint on the satellite configuration, since existing and proposed shroud dimensions demand a deployable antenna and deployment of the solar array to a position beyond the antenna extremities. The configuration shown in Fig. 9 includes an inflatable antenna reflector and two symmetrical solar arrays deployed with 4 telescoping tube assemblies. The satellite body is located in the vicinity of the antenna focal point, so that the feed location can be controlled from a sensor platform which is not separated from the feed by a soft structural link. The solar arrays are articulated and rotated by independent drive assemblies at the junction of the array with the antenna. In addition, separate propulsion units are located at this junction to provide for balancing of torque during thrusting modes.

The satellite accomplishes attitude control with a constant-speed pitch flywheel to provide orbit normal stabilization, a modulation flywheel for pitch control, sun sensors at the solar array for full orientation, and an rf interferometer for pointing of the antenna in a closed-loop mode. A cost breakdown of the system is shown in Table 4.

Subsystem	Weight, lb
Power	**708**
Receiver exciter	**14**
Transmitter	**232**
Antenna	**312**
Attitude control	**102**
Thermal control	**168**
Structure	**360**
Propulsion	**127**
Track, telem., cont.	**20**
Total	**2043**

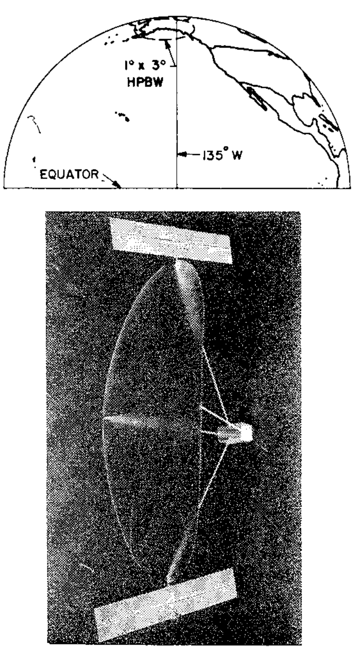


Fig. 9 Beam coverage and satellite concept—direct service to Alaska.

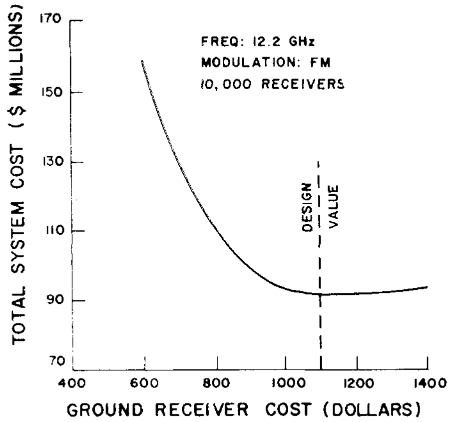


Fig. 10 System implementation costs—instructional service.

Cost comparison

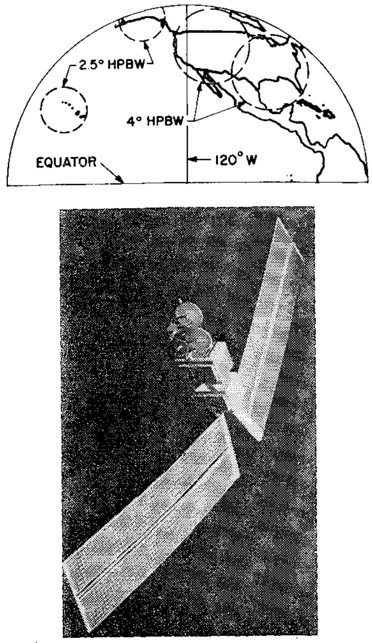
The terrestrial method of obtaining 3-channel service to all of Alaska is similar to the method previously described for India, and requires 60 stations with 100-mile spacing to cover the 0.6 million sq. miles area. The initial investment would be about $90 million for transmitting stations (assuming a cooperative use of transmitting facilities by the 3 channels), and $2 million for receiving antennas (based on 52,000 receiver installations requiring outdoor antennas with gain of from 2 db to 13 db). The annual operating cost (which includes a leased microwave relay network) would be $23 million; a total 10-yr program cost would then be about $320 million. The equivalent satellite system cost would be $155 million, based on a $100 receiver cost for 100,000 units and $145 million for satellite development and 10-yr operation. Thus, the cost of the terrestrial approach would be more than double the cost of the satellite.

Case III. Instructional Television for the U.S.

This service would enable developed nations to supplement present educational methods and establish cultural/educational adult community programs by use of receiving stations at locations such as schools and libraries. For the U.S., it is assumed to require 12 channels (6 to each of two areas). Two beams would be provided to the U.S. during morning and early afternoon hours; one to the eastern region and one to the west. When the eastern daytime programing is complete, the power used for U.S. transmission would be switched and divided among 2 previously inactive antennas aimed at Alaska and Hawaii. Daytime instruction for Alaska and Hawaii would then be possible for 5–6 hr. Afterwards, power could be switched back to the eastern U.S. for evening cultural/educational programs.

Optimum ground station receiver modification cost was based on total system implementation cost, since the project would likely be federally financed. Minimum system costs occur with frequency modulation of either X or S band. However, since the cost differences are small among operation at 2.5, 8.4, and 12.2 GHz, operation at 12.2 GHz was chosen since allocation of spectrum appears more probable in this frequency band. Figure 10 shows that the cost minimum point occurs at a ground receiving cost of $1100. This value was selected as the design point.

Positioning the satellite involved a trade study considering satellite beamwidth and subsatellite longitude. In many cases, in order to utilize circular beamwidths efficiently, it is desirable to displace the subsatellite longitude from that of the target area. Effective beam shaping is thus gained by creating an elliptical intersection of the conical radiation pattern and the spherical earth. It was determined that the location of 120°W would prevent satellite eclipse during the "prime"



Subsystem	Weight, lb
Power supply	248
Receiver exciter	52
Transmitter	160
Antenna	21
Attitude control	97
Thermal control	64
Structure	172
Propulsion	149
Track., telem., cont.	20
Total	983

Fig. 11 Beam coverages and satellite concept—instructional service to U.S. Beam axes: eastern U.S.: 47°N, 68°W; western U.S.: 47°N, 88°W; Alaska: 72°N, 156°W; Hawaii: 22°N, 162°W.

evening viewing hours, satisfy all other requirements, and balance out the slant range and ground elevation angles between Maine and Alaska. As shown in Fig. 11, the satellite can achieve coverage of the continental U.S. with two beams of HPBW = 4°, and cover Alaska and Hawaii with beams of HPBW = 2.5°. The beam axis coordinates are shown in Fig. 11.

The ground receiving equipment must provide bandwidth requirements for a 6-channel system. The preamplifier is assumed to handle three channels; consequently, the proposed design would use 2 preamplifiers, 2 frequency converters, and 6 demodulators. The resulting price for the 6-channel unit would be \$475 for a production quantity of 10^4. The characteristics of the ground receiving system components are presented in Table 3.

Satellite configuration

This satellite (see Fig. 11) is a sun/orbit-normal-reference system using an rf interferometer system to achieve antenna pointing accuracy of 0.05°. Two fully oriented roll-out solar arrays produce a prime power of 2.3 kw. A power conditioning compartment (or module) is fixed relative to the solar array and joined to the earthtracking transmitting module through a high-voltage d.c.-slip ring bearing to provide the daily 360° rotation. Seasonal tracking of the solar array is accomplished by a pivot on the power supply side of the slip ring. The use of d.c. rather than rf joints means much smaller losses than would be associated with rf joints at the *X*-band frequencies. The transmitting module contains the reference sensors and tracking electronics, transmitting subsystems for TV broadcasting, TT&C equipment, and a pitch flywheel to stiffen the roll and yaw stabilization. The broadcast transmitting antennas are fixed to one another, and the TWT power amplifier output will be switched by means of a mechanical rf switch/divider assembly in the waveguide feed system. System cost breakdowns are shown in Table 4.

Cost Comparison

Terrestrial methods of delivering the 6-channel Instructional TV signal are quite expensive. The model results in 211 stations at 119-mile spacing with installation costs of \$610 million for the stations and about \$0.5 million for receiving antennas (based on antenna installations ranging from about 22 db at 55 miles to about 2 db at 28 miles). Operation costs amount to about \$67 million annually; the total cost for a 10-yr program is then about \$1.28 billion.

Table 5 TVBS link calculations

Item	TV to India		Direct to Alaska	Instructional U.S.[a]
	Community	Distribution		
Frequency, GHz	0.8	8.4	0.8	12.2
Modulation	FM	FM	AM	FM
Maximum distance, 10^3 naut miles	20	20	22	21.55
Min. ground elev. angle, deg	53	53	7.7	18
TV standard, system	B	B	M	M
Picture, TASO grade	2	CCIR relay	2	1
Modulation index	1.5	6.2	...	5.1
IF noise bandwidth, MHz	35	101	6	61
Output S/N (weighted), db	39.5	56.0	39.5	50.5
Weighting and de-emphasis, db	−16.4	−16.4	−6.0	−12.5
Modul. improv., db	−15.6	−34.8	...	−32.9
Req'd IF N/N, db	7.5	4.8	33.5	5.1
Margin, db	1.5	1.5	1.5	1.5
Actual IF C/N, db	9.0	6.3	35.0	6.6
Threshold, db	8.8	4.8	...	5.1
Receiver syst. noise temp., °K				
Receiver and cable	290	175	330	175
Sky	35	152	45	202
Indigenous (man-made)	0	0	281[b]	0
Earth and ohmic loss	116	32	116	32
Total	441	359	772	409
System noise power, dbw	−126.9	−123.0	−131.9	−126.9
Receiving antenna				
Gain, db	−10.0	−48.4	−19.5	−47.7
Point loss, db	0.0	0.8	0.1	0.7
Polarization mismatch, db	0.5	0.5	0.5	0.5
Net gain, db	−9.5	−47.1	−18.9	−46.5
Carrier power req'd, dbw	−117.7	−116.9	−96.9	−119.7
Propagation loss				
Iono., Tropo., and refr., db	0.0	0.1	0.2	0.4
Fading, db	0.0	0.0	0.9	0.0
Cloud, db	0.0	3.0	0.0	0.9
Precipitation, db	0.0	0.4	0.0	4.3
Free space, db	182.5	202.5	182.7	206.2
Total	182.5	206.0	183.8	211.8
Required ERP/channel, dbw	55.3	42.2	68.0	47.3
On-axis signal strength, μv/m	122	18	420	24
On-axis power density $\times 10^{12}$, w/m²	39	0.8	470	1.5

[a] Worst case shown (eastern U.S.).
[b] Includes 252°K for low-elevation angle effect on main lobe.

Table 6 TVBS configuration summary

	Case I Community/distribution service to India		Case II Direct service to Alaska	Case III Instructional service to U.S.
Satellite weight, lb	752		2043	983
Booster (capability, lb)	Atlas E/Agena D/Kick (910)		Titan 3B/Centaur/Kick (2260)	Atlas E/Agena E/Kick (1150)
Satellite description	Fig. 7		Fig. 9	Fig. 11
Si solar cell panels	2 at 72 ft²		4 at 171 ft²	2 at 145 ft²
Total cell area, ft²:	124		621	259
Power level after 2 yr, kw:	1.1		5.5	2.3
Antenna				
Type and size:	2 concentric parabolas 21 ft (8 GHz), 2 ft (8.4 GHz)		Elliptical segment of paraboloid 29 ft × 80 ft	4 parabolas 2 at 1.4 ft; 2 at 2.25 ft
Construction:	Deployable (umbrella) and rigid		Inflatable wire grid	Rigid
Gain and HPBW:	Both 4.1° circular/32 db		1.1° × 3.1°/39 db	4.1° circ./32 db; 2.5° circ./36.3 db
Beam pointing (0.05° accuracy):	Antenna electrical axis using rf interferometer		Feed translation using rf interferometer	Orbit inclination for elevation control, rf interferometer for azimuth positioning
Transmitter type	CFA	TWT	CFA (separate video and audio)	TWT
Avg rf power output CH, w:	416	20	505	70 (max)
Over-all efficiency of transmitter system, %	58	35	42	34
Attitude control type	3 axis active-momentum wheel		3 axis-momentum wheel (flywheel augmented)	3 axis active-reaction control system augmented with pitch flywheel
Performance				
Satellite ERP/CH, dbw:	58	45	70	50 (max)
Field strength, μv/m:	122	18	420	24
(Req'd/act.) coverage area, 10⁶/mile²:	1.1/2.3		0.6/≈1.2	3/≈7.6
Picture quality (TASO grade/S/N):	2/39.5 db	CCIR relay/56.5 db	2/39.5 db	1/50.5 db
Audience size:	0.5 × 10⁶	100	10⁵	10⁵
Ground station cost ($):	50	2885	100	1100
Cost comparison—total 10-yr program				
Satellite ($ million):	87		155	95
Terrestrial ($ million):	151		325	1284
Terr. to sat. ratio:	1.7		2.1	13.5

The satellite system would cost $6 million for annual operation of the satellite, $24 million for the satellite development, and $11 million for receiver costs for the 10,000 installations. This amounts to a 10-yr program cost of about $95 million. Thus, the satellite approach is less expensive than the terrestrial by a factor of about 13.

If the systems were designed to reach all of the 100,000 schools in the U.S. (instead of the 10,000 school districts assumed) the satellite system cost would increase more dramatically than the terrestrial system: $100 million compared to $5 million for the 10-yr program. However, the cost ratio would still be about 7 to 1 in favor of the satellite system, and a full 100% of the area would be covered.

Link Calculations and Configuration Summaries

A compilation of the more critical elements of the link calculations is presented in Table 5. A system margin of 1.5 db was included to account for uncertainties of equipment performance and degradation. Table 6 is a summary of the significant configuration parameters of the three TVBS satellites.

Technology Improvements Needed

Certain major technological problems are common to all broadcast satellites. These are 1) generation and handling of high d.c. and rf power and voltage in the space environment, 2) the adequate dissipation and control of heat from high-power operation, 3) the deployment and orientation of large flexible structures, and 4) long-life reliability (2–5-yr goals).

Without cost and weight obstacles, all these problems could be resolved by a 1970 state-of-the-art subsystem. Since cost and weight are critical, however, additional technology improvement is required for the following items to attain low-weight, cost-effective systems.

High-efficiency output devices and associated rf components for high-power (kw levels) transmitters are still to be developed and space qualified. Solid state devices are limited by low-power gains resulting in low transmitter efficiency. Several NASA studies for klystrons, TWT, and CFA designs are in progress. The first phase of these studies is almost complete. The analyses show that efficiencies above 75% and life of 2–5 yr can be achieved. Gridded tubes, potentially lighter and cheaper at 800 MHz, are further along in development but require space qualification and high-efficiency amplifier development.

The power subsystem represents a high proportion of total system weight, volume, area, and cost. Developments of a 30-w/lb roll-up solar array using standard thin cells and a 20-w/lb fold-out array are currently being funded. These programs include prototype construction and test. The high labor costs associated with solar array fabrication makes manufacturing techniques for automatic cell laydown attractive. Nuclear power systems and systems employing thin film solar arrays are considered applicable only to later generation satellites due to the uncertainty of their availability. System considerations may indicate an advantage in developing high-voltage (e.g., over 200 v) solar arrays in order to ease power conditioner design requirements. Space technology for power conditioners at levels over 500 w is not too well known. The design data for the high-power d.c. and rf rotary joints required are presently limited in scope. The antenna problems are associated primarily with stowing, deploying, and pointing the large antenna structures required for certain missions. Beam-pointing, beam-shaping, and multibeam applications are being studied. Results of the ATS–F/G and AAP foldable truss antenna efforts have significantly advanced the state-of-art in large space antennas. Paraboloidal antenna reflector technology is well advanced, but antenna feed design needs to be further investigated for possible dielectric breakdown at high power levels. Mechanically steered arrays can distribute the high power over many elements, and redirective phased arrays offer significant advantages in satellite beam steering and attitude control requirements for the future. However, array advantages are offset by cost, weight, and efficiency penalties.

Flexible structure modes of vibration must be studied further to adequately assess problems arising in the deployment and construction of necessary appendages. A small number of configurations should be structurally modeled and analyzed (over suitable ranges of sizes and vibration modes) to provide a basis for establishing over-all satellite configurations and associated design criteria.

Thermal control for the power conditioner and high-power rf stages is particularly critical. Although heat pipes have been flown on Air Force and NASA programs, capacities over 2 kw need to be investigated for better data on critical (or burnout) heat flux so that feasible unit size limitations can be established. Thermal interface designs for transmitter output tubes are currently under study for NASA.

Finally, the TV ground installation cost becomes significant for large audiences so that low-cost TV frequency and modulation converters and ground antennas with appropriate gains in the 1–12 GHz range need to be developed. A NASA study to define, build, and test cost-optimized converters for this application is currently in progress.

Conclusions

These investigations and others have clearly shown that broadcast satellites are cost-effective for the whole range of potential applications in both direct and special services.

Even in cases where the signal is not aimed at direct reception in the home, there is no economic basis for the choice of high-cost ground receivers and low-performance satellites. Available technology can provide high-power satellites and low-cost ground receiving terminals. This makes broadcast satellites economically available for improved education and exchange of specialized professional information in developed areas, and for fundamental education and cultural efforts in developing areas.

Development of key elements of a high-powered broadcast satellite is in process. Ground converters are being defined and solar array power system development has been underway for many years. High-power transmitters and special antennas are being designed, and experience gained on current space programs is being applied to problems of control of large flexible vehicles and long life in space.

The high-powered broadcast satellite should be an integral part of total communications systems that will use both space and terrestrial elements to maximum advantage. The technology advances generated will also be applicable to the improvement of efficiency and economy of terrestrial systems.

There are many politico-technical problems associated with space broadcasting; however, none of them are unsurmountable. As the public becomes more aware of the benefits of this application of space technology, many of these problems will disappear. Steps should be taken now to create an environment that does not preclude making these benefits available to the peoples of the world.

References

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