A Technique for Controlling the Position of a Burning Solid-Propellant Sample in a Combustion Bomb

R. L. DERR* AND J. R. OSBORN†
Purdue University, Lafayette, Ind.

A method for controlling the position of a burning solid-propellant strand has been devised and used successfully in combustion bomb studies of solid propellants. A closed-loop servomechanism system moves a propellant strand at a velocity equal and opposite to the burning rate and locates the position of the burning surface with respect to a fixed reference point at any given time. Detection of burning surface position is accomplished through a visible light beam system in which a series of lenses directs light from a tungsten strip lamp over the surface. The fraction of light passing the strand is detected by a photomultiplier tube. Associated electronics convert the tube's output into the error signal needed to control the speed of a d.c. motor mechanically linked to the propellant strand. The system as designed works well with nonmetallized propellants, but modifications would be needed for use with metallized propellants.

Introduction

IN recent years, numerous studies of solid-propellant combustion have been conducted in pressurized combustion bombs. Although combustion bombs do not duplicate the thermal environment of a rocket motor, they do permit systematic changes in test environment which are not dependent upon the burning rate of the propellant sample. Moreover, the capability of testing small samples of propellants leads to cost savings and rapid turn-around in testing.

Probably the greatest complication in conducting combustion bomb studies is the movement of the burning propellant surface as the propellant sample is consumed. In measuring the burning rate as a function of pressure, that movement does not present a great problem. However, in studies wherein the reaction zone at or above the propellant surface is examined by a mechanical or optical probe, the movement of the propellant surface can present a formidable problem. If the probe is large compared to the size of the reaction zone of interest (e.g., film studies of strands of solid propellants), it is only necessary to sequence the recording equipment associated with the probe to the passing of the reaction zone. In most applications, this is not difficult and, indeed, is not necessary if the probe is maintained active over the time interval the propellant burns.

A more complicated situation exists where measurements within the reaction zone require the probe to be small compared to the size of the reaction zone of interest (e.g., spectroscopic studies of the gaseous reaction zone). Location of the probe within the reaction zone requires that the distance from the probe to a reference point (e.g., the burning surface) be known at all times. Furthermore, relative motion between the probe and the reference point limits accurate and meaningful measurements in the reaction zone to quantities which are independent with time. One technique that has been employed for such studies uses a probe that is fixed with respect to the combustion bomb, and the reaction zone of interest is allowed to burn past the probe. Knowing the propellant's burning rate and the time at which the front of the reaction zone reaches the probe station, one can calculate the location of the probe within the reaction zone as a function of time (see, e.g., Ref. 1). However, for valid results the burning rate must remain constant during the time period that the probe transverses the reaction zone. A second approach also depends on a fixed probe, but instead of relying on a prior knowledge of burning rate, high-speed motion picture records are employed in conjunction with the probe measurement to give spatial results (see, e.g., Refs. 2 and 3; variations of this approach could employ any of a variety of continuous burning rate measurement techniques along with the probe measurement[4]). These two approaches have a common limitation in that they rely upon single scans of the reaction zone. Thus, accurate and meaningful results can be obtained only if the combustion phenomena manifesting the quantity being measured remain constant with time. That condition is not realized in the reaction zone of composite propellants due to inhomogeneities of the propellant structure.

This paper describes a technique (Fig. 1) in which the propellant sample is moved so that the position of the reaction zone remains fixed with respect to the probe as the propellant

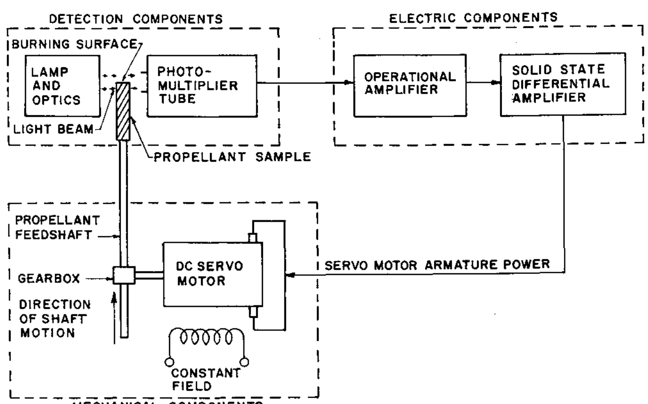

Fig. 1 Servomechanism component diagram.

Received December 23, 1968; revision received June 4, 1969. This work was supported by the U. S. Air Force Office of Scientific Research under Grant AF-AFOSR 207-63 and NASA under Contracts NsG 383 and NsG 592. The authors also wish to thank R. H. Wall and D. A. Flanigan of Thiokol Chemical Corporation, Huntsville, Ala., and W. Gin of Jet Propulsion Laboratory, Pasadena, Calif., for supplying the propellants used in this research program.

* Research Assistant; now Technical Specialist, Lockheed Propulsion Company, Redlands, Calif. Member AIAA.

† Professor of Mechanical Engineering. Associate Fellow AIAA.

burns. As a result, burning rate information is not required to determine the probe location within the reaction zone and the technique is not limited to a single scan of the reaction zone. The d.c. servomotor imparts a linear velocity to the propellant feed shaft equal and opposite to that of the burning surface of the propellant strand. The detection and electrical components supply the feedback to the servomotor. The detection of the surface is accomplished by a photomultiplier tube circuit that has an output proportional to the position of the burning surface within the confines of a visible light beam. The electrical components amplify this signal and provide power to the d.c. servomotor. Since the detection signal increases as the surface recedes in the direction of burning and decreases as the surface is driven in the opposite direction (at a speed greater than the burning rate), the burning propellant surface seeks a position of equilibrium dependent upon the gain of the operational amplifier.

Experimental Apparatus

Surface Detection Components

Figure 2 illustrates schematically the surface position detection system. Lenses L_1 and L_2 form an image of a glowing tungsten ribbon within the combustion bomb at the plane of the propellant strand. Lenses L_3 and L_4 magnify this image on a razor blade slit S_1 such that only a narrow portion (projected width of 50 μ) of the lamp image is detected by the position photomultiplier tube (hereafter referred to as the PPM tube). The width of the split S_1 then dictates the width of propellant surface seen by the PPM tube; the effect of burning surface tilt can be minimized by reducing width.

Thus, the feedback characteristics of the detection system can be readily seen. When the burning surface of the propellant strand is below the tungsten strip image, the PPM tube output is a maximum. If the burning surface is above the tungsten strip image such that the beam is blocked, the PPM tube output is zero. By proper design of the PPM tube circuit and the slit configuration, one can obtain a linear relationship between PPM tube output and position for intermediate positions of the burning surface. It was found that the lamp current could not exceed 12 amp, because at higher currents, the output of the PPM tube was saturated when the strand was not blocking the lamp image.

To permit discrimination between the radiation from the tungsten strip lamp and the luminosity of the combustion zone, the light beam emanating from the lamp is chopped at a low audio frequency (450 cps) before passing over the burning surface. By passing the PPM tube output through a blocking capacitor and a full-wave rectifier, the d.c. component due to the flame luminosity is eliminated, and the a.c. output originating from the chopped lamp luminosity is converted to a d.c. signal.

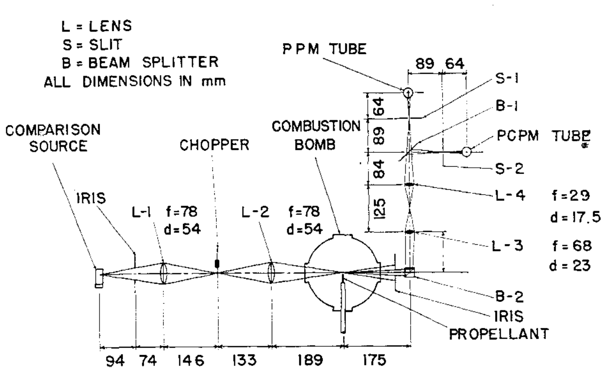

Fig. 2 Optical schematic of visible light beam position detection system.

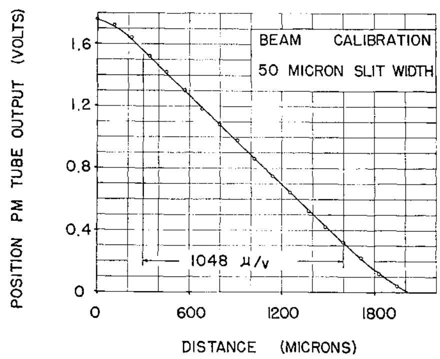

Fig. 3 Visible light beam position detection system calibration curve.

A typical calibration curve for the detection system is presented in Fig. 3. The plot depicts the rectified output of the PPM tube vs the distance traversed by a propellant sample at the lamp image formed within the combustion bomb. The curve is linear over its central portion, but nonlinearities are observed near the edges of the lamp. As a result, it is necessary to confine the operation of the system such that the propellant surface remained in the central portions of the tungsten strip image.

The calibration technique is to advance the surface of an unburning propellant strand into the image of the tungsten strip lamp by known distance increments and record the output of the PPM tube after each advancement. The height of the lamp image is approximately 2 mm, and it is convenient to use an advancement increment of 114 $\pm$ 5 μ, corresponding to ¼ turn of the servomotor driveshaft. The small error in position resulted by applying a downward pressure to the propellant feedshaft and revolving the servomotor driveshaft such that the feedshaft moved upward only. Thus the uncertainty in the distance measurement is $\pm$ 5 μ, provided the output of the PPM tube was not attenuated from sources other than the surface of the propellant blocking the tungsten lamp image.

To detect the presence of an error in the PPM tube output due to smoke or haze attenuating the tungsten lamp light beam, a second photomultiplier tube, termed the position correction photomultiplier tube (hereafter referred to as the PCPM tube), is incorporated in the detection system. It is adjacent to the PPM tube (Fig. 2), and its output is passed through a separate photomultiplier tube circuit, blocking capacitor, full-wave rectifier, and smoothing capacitor. The PCPM tube views, by means of a beam splitter and slit S_2, the same narrow portion of the lamp imaged viewed by the PPM tube. However, this slit, is further restricted, over the slit S_1, to allow only the upper portion of the narrow image to enter the PCPM tube. That is, the PCPM tube views a region of the lamp image which is not interrupted by the surface when the system is operating satisfactorily.

By recording the PCPM tube output before igniting the propellant strand and monitoring its output during the burning of the strand, it is possible to determine the time at which attenuation occurs due to window clouding and excessive light scattering in the flame zone. Thus, a means of knowing when the detection system yields an unreliable signal is available during a test.

Electrical and Mechanical Components

The electronics for the servomechanism system consist of the photomultiplier tube circuit, the operational amplifier, and the differential amplifier as shown in Fig. 4. The photomultiplier tubes are both RCA Model 931A tubes whose load resistance is adjusted for maximum linearity by means of separate 1-MΩ potentiometers linked by blocking capacitors

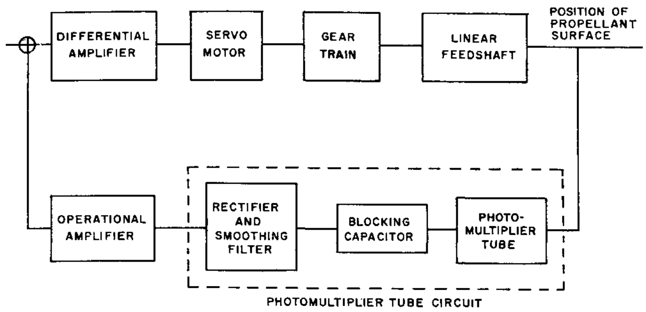

Fig. 4 Block diagram of electrical components.

to the primary windings of an interstage transformer. The function of the transformer in both cases is to isolate the photomultiplier from the respective rectifier bridges, allowing full-wave rectification of the a.c. voltage developed across the load resistors.

The operational amplifiers permit wide variations of the gains of the photomultiplier tube circuit outputs and serve as high-impedance couplings between the photomultiplier tube circuits and other associated electronics. In the case of the PPM tube circuit, two operational amplifiers are employed so that the rectified output can be monitored. The PCPM tube circuit output is linked to a single operational amplifier, and the output of this amplifier also is monitored. The differential amplifier derives power for the d.c. servomotor armature by combining two full-wave rectifier bridges in parallel. The power is controlled by triggering silicon rectifiers in a bridge in such a manner that the integrated voltage output to the motor armature is linear with respect to the signal received from the PPM tube operational amplifier. When the latter signal is received, the differential input causes the trigger circuit to fire the SCR's in the SCR circuit, and power is delivered to the armature. A complete description of the electrical components may be found in Ref. 5.

The angular rotation of the d.c. servomotor is transmitted to a worm gear located in the gear reduction box. The worm gear drives an internally threaded gear, which in turn drives the threaded propellant feedshaft. A bar mounted on the feedshaft perpendicular to the feedshaft axis prohibits the feedshaft from revolving when a torque is applied to the internally threaded gear. Since the propellant feedshaft is driven into a pressurized combustion bomb and the motor always revolves in the same direction when a propellant strand burned, backlash is not a problem in the gear train.

Burning rates of propellant samples are measured from the output of a tachometer incorporated in the servomotor. The tachometer is calibrated such that the speed of the propellant feedshaft is known as a function of the tachometer output.

Determination of Temperature Profile

Although such a system as described here can be used as a *primary standard* for determining burning rates of nonmetallized solid propellants, the purpose for which the system was designed was to attempt to measure the temperature profile above a moving, burning surface. This requires that two parameters be determined: a) the distance from the burning surface to the temperature measurement region and b) the size of the temperature measurement region.

The size of the temperature region was determined by the projected image of the monochromator entrance slit in the flame. Since the direct measurement of the size of the slit was difficult and the calculation of the projected image in the flame was inaccurate, a calibration technique was devised which allowed the direct recording of the size of the temperature measurement region for that particular slit width. The procedure was first to locate the unburned propellant surface below the comparison source beam such that the photomultiplier tubes detected the full beam of light from the comparison source. Second, the strand was driven upward and the outputs of the photomultiplier tubes were recorded. A typical output of this type is shown in Fig. 5. At time $t = 0$, the propellant surface is located below the comparison source image and at a later time, the strand has been driven upward such that the light entering the temperature measuring photo multiplier tube (hereinafter called TPM tube) has been blocked. By measuring the output of the PPM tube from the point where the surface first begins to block the light detected by the TPM tube to the point where all light detected by the TPM tube is blocked, a voltage change for the PPM tube is known which can be converted to a distance change by referring to the calibration curve shown in Fig. 3. Thus, in the sample shown, the voltage change is 2.5 v, and the temperature measurement region is 50 μ in height above the surface. The accuracy of the size of the region depends upon the calibration of the PPM tube; that is, $\pm 5\ \mu$.

To obtain a temperature profile above the burning surface of a strand of propellant, it was necessary to measure the distance from the burning surface to the region of temperature measurement for each temperature measurement. This distance measurement was obtained from the output of the PPM tube as illustrated in Fig. 6. At time $t = 0$ the burning surface of the propellant sample was located above the temperature measurement region; as a result, the TPM tube output was zero. The movement of the surface at time $t = 0$ is indicated by the increasing output of the PPM tube. At time t_1, the surface was located at the upper edge of the temperature measurement region. As the propellant continued to burn, the TPM tube output increased until the region was no longer blocked. The time t_2 at which that occurred is determined from the change in the PPM tube output which corresponds to the size of the temperature measurement region (see Fig. 5). At $t > t_2$, the output of the PPM tube is utilized to calculate the distance from the center of the temperature measurement region to the burning surface. This is accomplished in terms of the voltage change as indicated at time t_3 in Fig. 6. Once the voltage change is known, the slope of the PPM calibration curve, Fig. 3, gives the actual distance of interest. It should be mentioned that this procedure is only valid when the PCPM tube output is a maximum, because the PPM calibration curve is not valid when the comparison source beam is attenuated by anything other than the propellant surface.

Experimental Results

Operation of the servomechanism system was demonstrated through tests using small propellant samples burned in the combustion bomb. Two propellants were used in the experi-

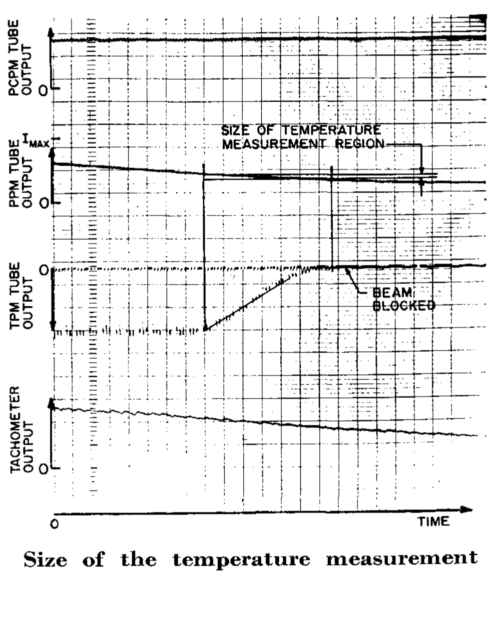

Fig. 5 Size of the temperature measurement region.

ments. They were simple nonmetallized rubber-base types, 40% polysulfide binder and 60% ammonium perchlorate (AP), containing narrow-cut oxidizer grind distributions. One propellant contained 6-μ-mean-diam AP, whereas the second contained 50-μ-mean-diam AP. The propellant samples were cut to dimensions of 4 in. $\times$ 0.5 in. $\times$ 0.0625 in. and inhibited on all sides by leaching the oxidizer crystals from the surfaces with warm water. The samples were mounted in a viselike fixture on the end of the propellant feedshaft and ignited with a hot wire. The outputs of the PPM tube, PCPM tube, and tachometer were recorded during operation of the servomechanism system, and motion pictures (64 frames/sec) showing movement of the burning surface were made using a 16-mm Paillard-Bolex camera.

Typical results from a test at 100 psig using the propellant containing 6-μ AP are presented in Fig. 7. The propellant sample was initially positioned so that the light emanating from the modulated source was blocked by the side of the sample. Thus, outputs of the PPM and PCPM tubes are zero at time t_0. Ignition occurred at time t_1. At time t_2, the burning surface reached the modulated light beam, and as the surface continued to burn, the light received by the PPM tube increased until error signal was received by the differential amplifier, causing the servomotor to drive the propellant sample into the light beam. Oscillations in the PPM tube and tachometer outputs indicated that the gain of the system was too high, leading to an underdamped system. In other words, the burning surface "overshot" the equilibrium position dictated by the reference signal. At time t_3, the outputs of the PPM tube and the tachometer were steady indicating that the equilibrium position was attained.

The output of the PCPM tube achieved a maximum fixed value following time t_2. That level of light establishes the PCPM tube output resulting from an absence of attenuating factors. At time t_4, a sharp reduction was noted in the PCPM tube output followed by changes in the PPM tube and tachometer outputs. The indication here is that the modulated light has been attenuated.

Comparison of the data of Fig. 7 to photographic records of the sample movement showed excellent correspondence. Surface oscillations at $t_2 < t < t_3$ were observed; similar oscillations were observed from the photomultiplier tube outputs. At t_3, the surface remained fixed, and at t_4, the window clouding precluded accurate detection of the surface.

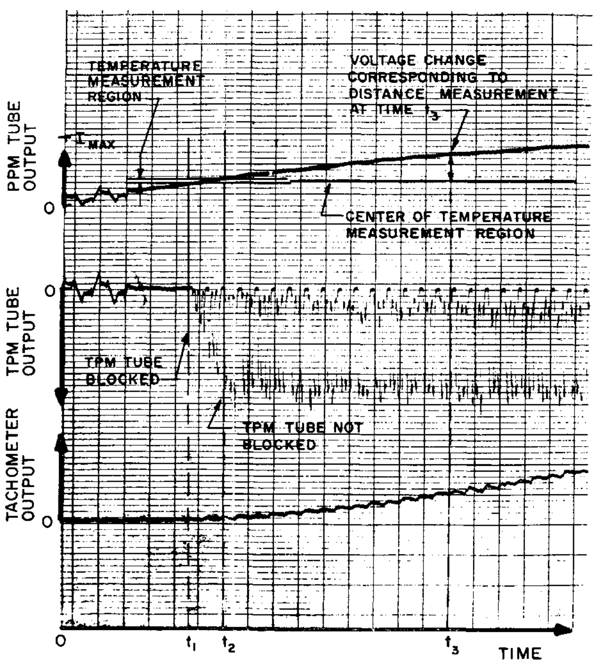

Fig. 6 Measuring distance from the PPM tube output.

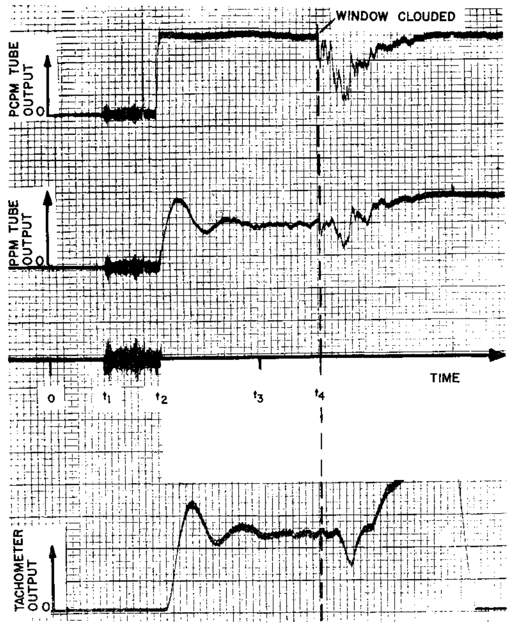

Fig. 7 Temperature measurement system data output.

Conclusions

The servomechanism system as described is best suited for steady-state spectroscopic studies of nonmetallized propellant combustion. In that application, the features of locating the probe position in the reaction zone of interest and of eliminating the severe limitations imposed by a single scan of that zone make this a valuable instrument.

Remaining shortcomings of the servomechanism deserve attention. First, the detection system is susceptible to error when sources of light attentuation are introduced in the light path within the combustion bomb during a test. For this reason, the present system is not satisfactory for studies of metallized propellants where positioning of the burning surface and accurate measurements of its location are of interest. To adapt the system to operate with such propellants, it would be necessary to replace the tungsten strip lamp with a source having a higher intensity (such as a laser) and to determine attenuation of the light source due to scattering by carefully calibrating the PCPM tube. This would then provide a correction factor which could be applied to the PPM tube output allowing position measurements.

A second factor that limits the use of the servomechanism system is the response of the motor speed to rapid fluctuation in the sample position. This limitation is not important in studies of steady-state burning. However, studies of combustion phenomena dealing with rapid pressure changes (e.g., combustion pressure oscillations, extinguishment due to rapid depressurization, etc.) are not possible in the present system. To establish these limitations, a stability analysis of the system would be necessary. Such an analysis was not conducted for the system; however, step-input response tests of each component in the system showed that the rectifier and filter circuit of the PPM and PCPM tubes had the greatest response time in the system. The time constant for these circuits was about 50-msec/for a 3-v step input. Thus, neglecting the possibility of instabilities in the system, the maximum frequency allowable is about 200 cps.

References

[1] Penzias, G. J., Liang, E. T., and Tourin, R. H., "Infrared Radiation and Temperature Measurements in Solid Propellant Flames 1. Preliminary Study of Arcite 368," TR-800-5, 1962, Warner and Swasey Co., Flushing, N. Y.

[2] Austin, T. D., "Flame Temperature Profile of Ammonium Perchlorate Fuel Binder Sandwiches," 4th ICRPG Combustion Conference, Menlo Park, Calif., 1967.

[3] Sutherland, G. S., "Mechanism of Combustion for Ammonium Perchlorate-Polyester Resin Composite Solid Propellant," Ph.D. thesis, 1956, Aeronautical Engineering Dept., Princeton Univ., N. J.

[4] Hermance, C., "Continuous Measurement of the Burning Rate of a Composite Solid Propellant," *AIAA Journal*, Vol. 5, No. 10, Oct. 1967, pp. 1774–1777.

[5] Derr, R. L., "An Experimental Investigation of the Gaseous Phase Reaction Zone in a Composite Solid Propellant," Ph.D. thesis, 1967, Purdue Univ., Lafayette, Ind.

OCTOBER 1969 J. SPACECRAFT VOL. 6, NO. 10

An Evaluation of Television Broadcast Satellite Systems

R. W. Hesselbacher*
General Electric Company, Valley Forge, Pa.

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

Presented as Paper 68-1061 at the AIAA 5th Annual Meeting and Technical Display, Philadelphia, Pa., October 21–24, 1968; submitted November 25, 1968; revision received May 7, 1969. The technical aspects of this evaluation supported in part by NASA Lewis Research Center Contract NAS 3-9708.

* Manager, Communications Satellite Programs, Space Systems Organization, Missile and Space Division. Member AIAA.