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Advanced Technology for Direct TV-Broadcasting Satellites

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This paper presents a survey of some of the technological developments carried out in W. Germany over the past few years in order to prepare for the development of a direct TV-broadcasting satellite (TVBS). Specific requirements for operational TVBS such as high pointing accuracy (0.05 deg), large solar arrays (4-10 kW), high-power traveling wavetubes (TWT's), large antennas, etc., need advanced technology to allow for an efficient spacecraft design in the 1000 kg BoM class (beginning of mission). Technical features as well as the development status are described for the following systems: the advanced lightweight ULP (ultra-lightweight panels) solar array, the unified propulsion system (UPS), and the electrical thruster system for orbit control RITA-1 and 2 (radio-frequency ion thruster assembly).

Introduction

THE World Administrative Radio Conference (WARC), in January 1977, established the fundamental requirements for direct TV-broadcasting satellite (TVBS) service in Europe and other parts of the Earth. The definition comprises the downlink frequencies (within the 11.7-12.6 GHz band), the number of channels (five in general), and the (elliptical) coverage areas with the maximum receive power at the edge for each country (90-cm-diameter receive antennas). The latter defines the maximum radiated power from the satellite transponder. In the case of W. Germany, it has been calculated to be 260 W; the fully redundant five-channel transponder, therefore, requires some 3.7 kW input power. For other countries, such as Italy or France, it requires about 5 kW, and for Scandinavia even more.

Figure 1 shows the requirements for TVBS in terms of payload mass and power. In particular the power demand is much higher than for regional or global communication satellites. For a conventional spacecraft with subsystem technology as used in Intelsat V, the communication payload capability would almost disappear for power levels above 4 kW (see Fig. 1).

The solution is either to go to a larger spacecraft and a more expensive launch vehicle [Shuttle + Inertial upper stage (IUS)] or to apply advanced technology and keep the spacecraft in the 1000 kg class, compatible with the European Ariane launcher or the Shuttle + SSUS-A. Another specific user requirement for TVBS is the standby satellite, immediately available in case of a spacecraft failure to avoid interruption of the TV-program broadcasting.

The economic optimization led to the operational philosophy of a 10-12 year spacecraft bus lifetime and a 5- 6 year transponder design lifetime, i.e., each spacecraft first serves as standby for 5 years and then the transponder is switched on for another 5 years. This philosophy reduces the number of spacecraft and launches by some 30% compared to a system with two satellites with 7 years lifetime each. This fact, as well as the overall trend to increased spacecraft lifetime for operations cost reduction, adds another burden to the spacecraft capability by taking into account that each year 20-25 kg more mass is required for the attitude and orbit control system (unless one uses ion thrusters).

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The Rationale for New Technology

It is a well known principle that new technology is not introduced unless absolutely necessary. In case of the TVBS, however, there is a must for 1) the radio-frequency attitude control sensor (to achieve the 0.05 deg pointing accuracy), 2) an essential mass reduction in subsystems to allow for the required payload in spite of the present Ariane launcher performance limit of about 1000 kg BoM (beginning of mission), and 3) a reliable long-term spacecraft bus lifetime (10-12 years) to allow economical operation of the system. In a more specific way the new technology items and their contribution to the aforementioned goals are shown in Table 1. The effect of new technology on the available payload mass and simultaneously on extended bus lifetime is essential, as shown in Table 2.

In Fig. 1 the impact on a 1000 kg TVBS is shown by the TV-SAT payload-power curve compared to the Intelsat V capability. The improvement achieved by more advanced subsystem technology is described in the following sections.

The final argument for the introduction of advanced technology is economics—even though the new subsystems and more redundancy for increased lifetime lead to a more expensive spacecraft, program economics will be improved considerably because of a lower number of spacecraft and launches required for an operational service. Figure 2 shows the complex interaction of spacecraft lifetime, transponder

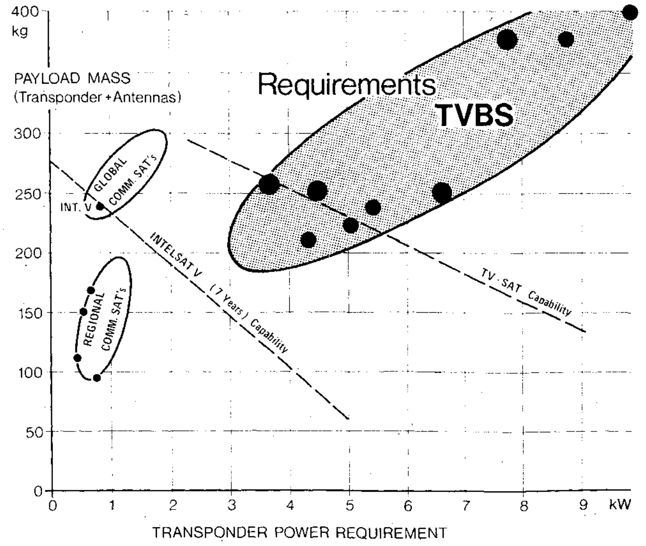


Fig. 1 Direct television broadcast satellite (TVBS) requirements in terms of payload mass and power and spacecraft capabilities (Intelsat V vs TV-SAT).

Table 1 **Improvements by new technology**

Goal	Unified propulsion system	Hybrid RCS	RF-sensor	Lightweight solar arrays and batteries
Bus mass reduction (more payload)	X	X		X
Longer lifetime in orbit	X	X		X
Higher pointing accuracy			X	
Lower specific cost	X	X		

Table 2 **Effects of new technology on payload and lifetime increase (1000 kg BoM spacecraft)**

	Intelsat V	TV-SAT	
Example	Conventional technology	Present technology	Advanced technology
Comm. payload for a 4.5 kW transponder power requirement	80 kg	170 kg	250 kg
Typical bus lifetime	7 yr	7-10 yr	10-12 yr
Solar array	CFC-sandwich (ICS)	Hybrid array (ULP)	...with 50 μ cells
Propulsion	Solid ABM + hydrazine RCS	Unified bipropellant system (UPS)	...plus ion thrusters for orbit control
Attitude control and sensors	Spin-transfer IR-sensor 0.1 deg pointing accuracy	Three-axis stabilized transfer	Rf-sensor 0.05 deg pointing accuracy

capability, total mass, and cost. The key factor for the user organization is C^* = cost per channel and year. These specific TVBS space segment costs are defined more precisely as follows:

$$C^* = \frac{C_S + C_L}{L \cdot N(R_L \cdot R_{PL} \cdot R_{bus})}$$

with

C_S = spacecraft recurring cost (flight unit cost)
C_L = launch cost
L = operational transponder lifetime
N = number of TV channels per satellite
R_L = launch vehicle reliability
R_{PL} = payload reliability
R_{bus} = spacecraft bus reliability

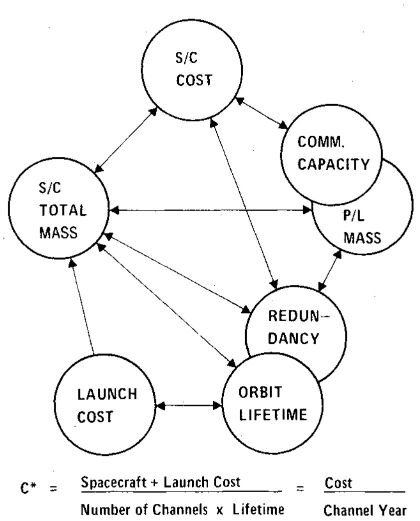


Fig. 2 **Interaction of main design parameters of TVBS for economic optimization.**

It is evident that lifetime and transponder capability have a major impact on the specific cost. This satellite design optimization for minimum program cost is a deviation from the conventional approach of first establishing the payload specification and then trying to "fulfill the specs" by a proposal. The application of advanced technology in combination with system optimization definitely leads to an essential improvement in system economy.

The Unified Propulsion System

The standard solution for geosynchronous spacecraft in the past was a solid-propellant apogee motor and a hydrazine thruster system for attitude and orbit control. The European Symphonie satellite for the first time used a bipropellant liquid apogee motor and bipropellant thrusters for attitude and orbit control. The MMH/N_2O_4 combination means a lower propellant mass requirement because the specific impulse of the 10-N thrusters (285 s) is superior to the performance of hydrazine thrusters (220 specific impulse). The apogee motor with 400-N thrust level even achieved a performance of 306 s specific impulse.

The low-thrust apogee injection mode has advantages compared to a high-thrust solid apogee boost motor (ABM) especially if the spacecraft has large appendages like antennas and/or booms. In addition, the low-thrust injection allows a three-axis stabilized (nonspinning) transfer and injection mode, thus eliminating dead masses for spin balance and a nutation damping system.

After successful demonstration of the new bipropellant technology and in recognition of the requirements for TVBS with large antennas, the logical next step was the combination of apogee motor and reaction control system (RCS) into one single system, the unified propulsion system (UPS). The combination not only means savings in hardware components mass and cost but also reduces the total amount of propellants by the higher performance and greater system flexibility. Propellants can be used for any maneuver, such as transfer, apogee injection, acquisition, orbit control and attitude control. Specific margins and residuals for each maneuver and/or system are no longer required. The UPS not only

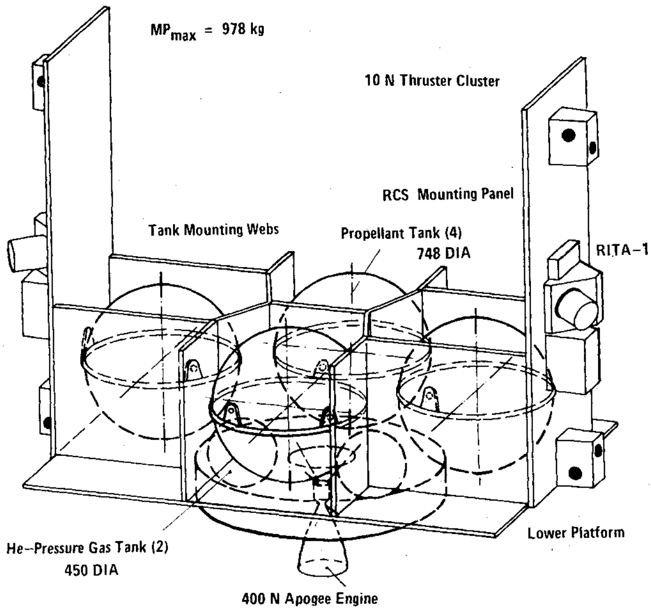


Fig. 3 UPS combined with ion thruster packages in a separate satellite propulsion module.

means a mass reduction in the order of 20-40 kg compared to conventional solutions but it also eliminates one complete subsystem—the ABM—with a relevant reduction in system management, control and test effort.

The first UPS in the size and configuration as required for a 1000 kg TVBS is under development for the Galileo Jupiter Orbiter. The same system with identical tanks and engines is foreseen for the German TV-SAT spacecraft. Figure 3 depicts the satellite propulsion module with four propellant tanks, one main engine and 14 small 10-N thrusters. This concept allows for separate integration and testing. The overall UPS system schematic is shown in Fig. 4. It is a completely redundant system with two branches of seven thrusters each.

The apogee maneuver is performed under controlled tank pressure (15 bar) while the subsequent long-term operation of the small thrusters is performed in the blowdown mode. The tanks are designed for a propellant capacity of up to 975 kg, thus meeting the requirement of both the Ariane launcher (693 kg) and the Shuttle/SSUS-A (825 kg) for apogee injection as well as additional volume for on-orbit propellants. Another demonstration of the UPS design flexibility is that 1) the same system can be used for two launchers with different injection velocity requirements; and 2) the tanks are large enough to allow a final fillup on the launch site to the maximum allowable spacecraft mass—thus utilizing any available mass margin for additional lifetime and/or performance margin.

The engines being used are flight-qualified on two Symphonie satellites and have been improved by extending the nozzle of the 400-N thruster for greater performance and by equipping the 10-N thruster with Moog valves to reduce costs, replacing the extremely small and lightweight but expensive valves used originally, see Fig. 5.

The engine's main data are summarized in Table 3. The engine's performance and loss mass is outstanding, compared to other engines in this class. This is due mainly to the application of a combined cooling system: film cooling of the chamber, regenerative cooling of the throat section, and radiation cooling of the nozzle. Only by this method can the heavy design of ablation/cooling be avoided.

Attitude Measurement and Control System

Several new features have been introduced to the attitude measurement and control system (AMCS) both for operations

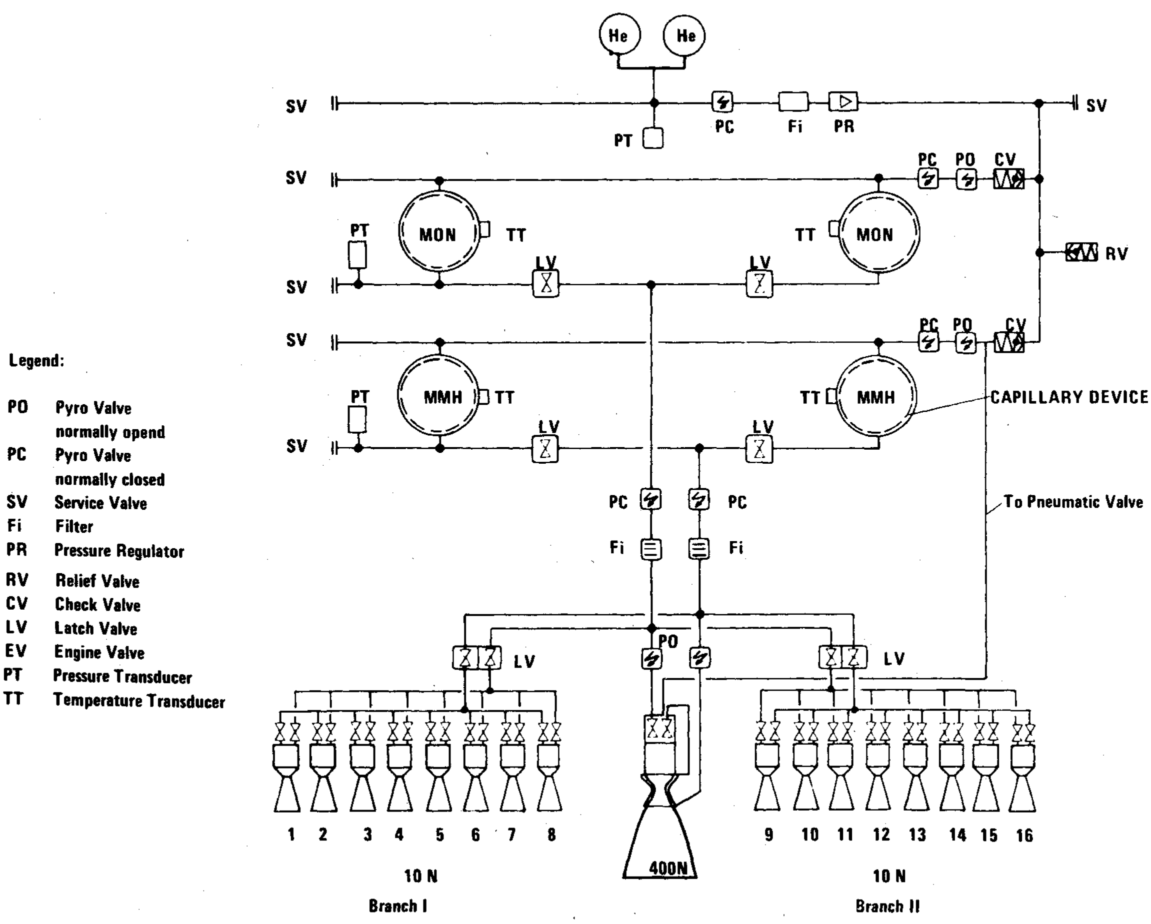


Fig. 4 UPS schematic.

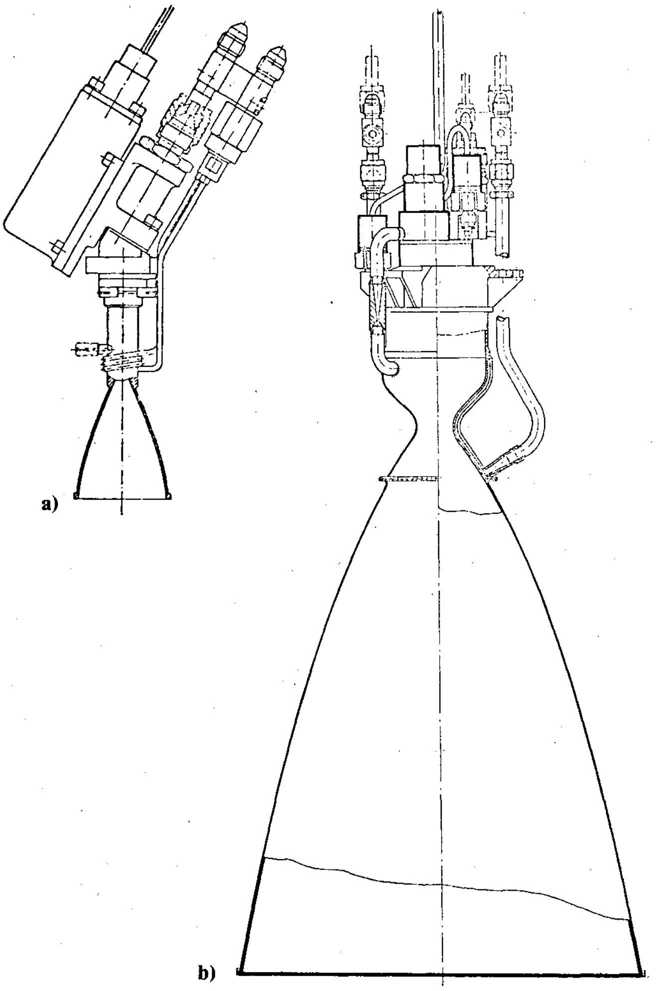


Fig. 5 The bipropellant high-performance thrusters for the UPS as being used for the Galileo project. a) 10-N thruster BT-10G with Moog valve. b) 400-N thruster BT-400G with extended nozzle.

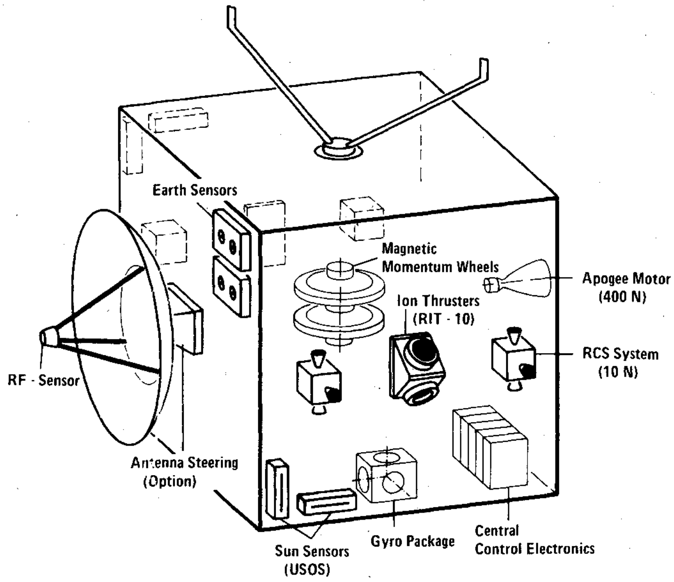


Fig. 6 Advanced attitude and orbit control system components.

and the hardware (components). As mentioned previously the requirement for a spinning mode during transfer from low orbit (LEO) to geosynchronous orbit (GEO) disappears if a solid ABM is not being used. The switch to a three-axis stabilized transfer eliminates the need for special IR and Sun sensors as well as for a nutation damping system (some 5 kg mass saving). In addition a balance mass of 10-20 kg is no longer required, as well as the associated spin balance testing.

In the future, the spin-balance requirement will become more and more a severe design restriction, considering the more complex and larger antenna systems expected. Also it seems awkward to apply a spin-stabilized mode to be used only for a few hours during a 10 year mission. The alternative solution of a passive transfer with the IUS, for example, results in lowest cost and weight for the spacecraft; however, the launch cost is much higher.

Table 3 Bipropellant engines data summary

	400-N thruster	10-N thruster
Propellants	N_2O_4(MON-1) + MMH	N_2O_4(MON-1) + MMH
Mixture ratio	1.64	1.64
Expansion ratio	1:1500	1:2000
Specific impulse	309 s	285 s
Chamber pressure	7 bar	8.7 bar
Engine length with valves	54.0 cm	15 cm
Nozzle diameter	24.8 cm	2.93 cm
Engine mass incl. valves	2.7 kg	0.360 kg
Number of engines built	27	53
Maximum burning time of a single engine	285 min	315 min

New digital Sun sensors have been developed that are suited both for transfer, acquisition and on-station, as well as digital control electronics. Another new component is the double-gimballed redundant flywheel considered to be more efficient in mass and power requirement than a four gyro assembly. Figure 6 illustrates these new components.

The most essential new sytem required to fulfill the 0.05 deg pointing accuracy of a TVBS is the radio-frequency sensor (rf-sensor). A mode-coupler is integrated into the feed system of the transmit antenna and beam deviations from the signals of a ground beacon are derived by a special tracking receiver system. By this arrangement all misalignments and deformations between transmit antenna and IR-sensor location are avoided. In case of two different transmitting antennas, one antenna needs a gimbal mechanism in order to perform corrections without disturbing the other antenna rigidly mounted to the spacecraft structure.

Ion Thrusters for Orbit Control

For larger spacecraft and extended lifetime in orbit the propellants for orbit control (stationkeeping) become an increasing burden to spacecraft performance. This is especially the case for TVBS with 0.1 deg stationkeeping accuracy and large solar arrays which create an additional demand for east-west corrections. The N-S stationkeeping propellant requirement depends mainly on spacecraft mass (about 25 kg per yr for a 1000 kg satellite) while the E-W stationkeeping propellants depend mainly on the solar array size, i.e., 2 kg per yr for a 3 kW array and 5.5 kg for a 9 kW array.

Calculating the total propellant requirement for a 1000 kg, 6-kW TVBS with 10 year lifetime the total mass is 210 kg bipropellants or 260 kg hydrazine (including attitude control and acquisition). Together with the associated hardware this amounts to 25-32% of the total spacecraft mass. For a desirable 12 year lifetime the share would go to a prohibitive 30-37% of the total mass (Fig. 7).

The only means for an essential reduction in propellant mass is the use of ion propulsion. Therefore, in W. Germany the RIT-10 radio-frequency ion thruster in the thruster range 5-10 mN has been developed. Because of the high specific impulse (31,000 Ns/kg) only 1.85 kg mercury are required for N-S and 0.15-0.4 kg for E-W stationkeeping per year.

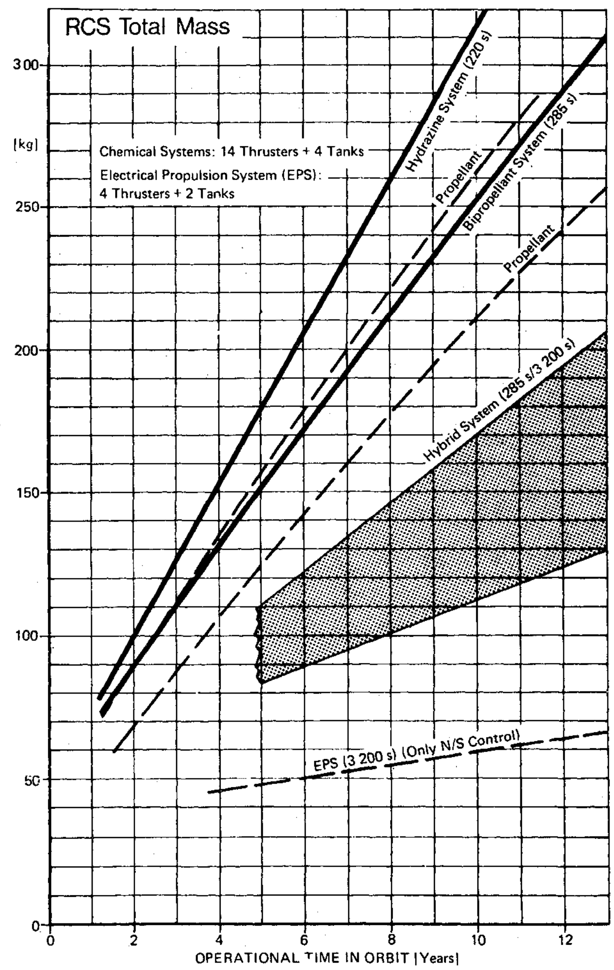


Fig. 7 Reaction control system mass vs orbital lifetime for a 1000 kg spacecraft.

(RIT = radiofrequency ion thruster). The RIT-10 engine has more than 20,000 hs elapsed ground test time; one single engine has been tested continuously over 8000 hs which is equivalent to 11 years orbital operations (157 min per day excluding eclipse periods). The ion thruster main data are summarized in Table 4. The RITA-1 package has been conceived as a complete thruster unit to be mounted externally onto the spacecraft wall. The package consists of the thruster

Table 4 RIT-10 ion thruster data summary

Thrust level	5 to 10 mN
Exhaust velocity	38,000 m/s
Effective specific impulse	31,000 ns/kg
Propellant (mercury) mass flow	0.33 mg/s
Acceleration voltage	1500 V
Beam current (10 mN thrust level)	126 mA
Drain current	< 3mA
Thruster power requirement	290 W
Thruster mass	1300 g

RIT-10 plus propellant tank, rf-generator, control/power electronics and the associated structure and thermal control. The total mass is 26.4 kg. It is foreseen that two of these units will fly on the first (pre-operational) TV-SAT for flight qualification (Fig. 8).

A fully operational system, however, requires a further step in system integration, simplification and cost reduction: RITA-2 is a completely redundant package with two engines, a system mass of 38.6 kg, 700 W power demand, and a propellant capacity of 12.5 kg, sufficient for 10 years of orbit control for 1000 kg satellites. Two RITA-2 packages are required per spacecraft mounted on the E-W panels.

The introduction of these ion thruster units for operational spacecraft leads to a RCS mass reduction of more than 100 kg. However, the demonstration of an adequate orbital lifetime has still to be performed and, therefore, the intermediate step of a "hybrid system" has been conceived (shaded area in Fig. 7).

In this case a good share of the orbit correction capability is left with the bipropellant (unified) system. This reduces the weight advantage, but increases the overall reliability. This approach allows the failure of one or two ion thrusters without endangering the orbit control capability. It also allows performance during the last two years of orbital operations, when the solar cells' degradation has processed so far that power is no longer available at certain periods. This approach avoids an increase in solar array size and is much more cost effective. Propellants are cheaper than solar cells!

Advanced Hybrid Solar Array

The aluminum structure initially used for solar arrays was replaced by the development of the "improved composite sandwich" (ICS)—aluminum-honeycomb panels with woven carbon-fiber composite face sheets. These rigid panels, with much greater stiffness, are being used on ESA's OTS spacecraft and the Intelsat V series of satellites (Fig. 9).

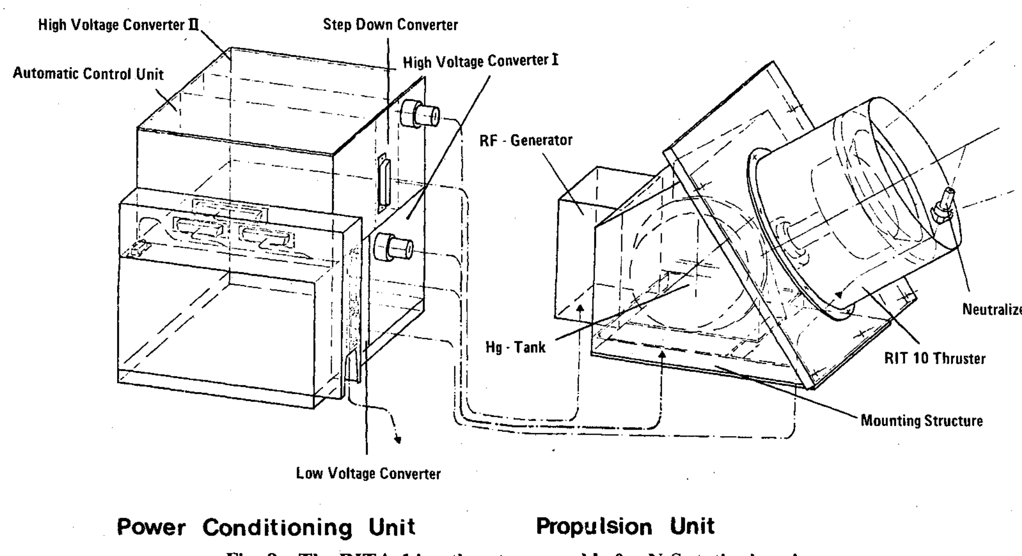


Fig. 8 The RITA-1 ion thruster assembly for N-S stationkeeping.

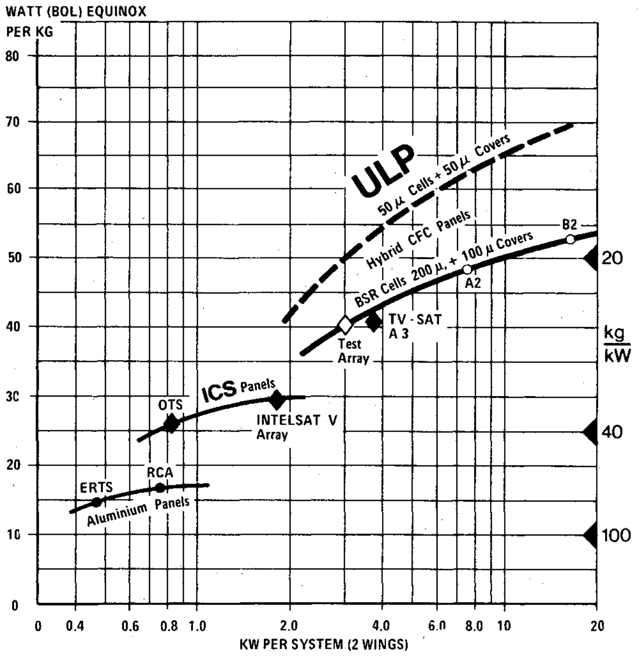


Fig. 9 Solar array specific performance vs size.

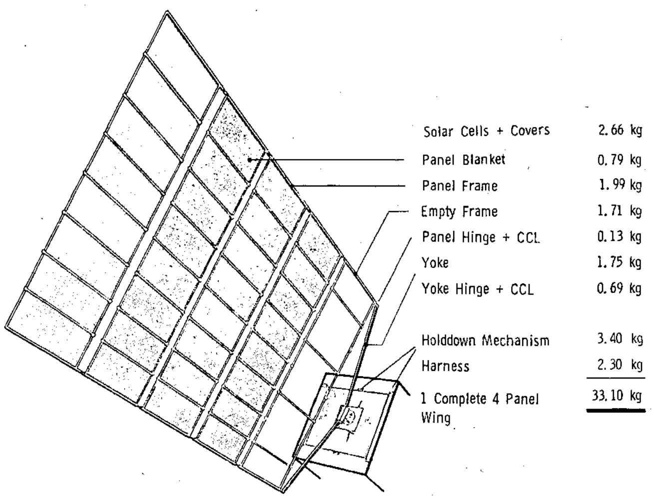


Fig. 10 The ULP solar array component and mass definition.

Another major improvement in mass reduction was achieved with the development of the ultra-lightweight panels (ULP) solar array. This unique design is comprised of rigid carbon-fiber composite frames and flexible CFC-Kapton substrates for the solar cell coverage. The substrates are pretensioned by adjusted springs at the short sides of the panels. The single panel size is 1.1 × 3.3 m and the feasible range of array size is 2-20 kW, covering the requirements of future TVBS.

To illustrate the mass saving achieved by this new solar array, a TVBS with 6 kW power BoM would have a solar array mass of 193 kg with the ICS rigid panels, but only 128 kg with the ULP array (a difference of 65 kg in favor of payload).

The ULP array has been qualified by an extensive series of tests including a deployment test in a large space simulation chamber. A four-panel wing has been built with a supporting technology contract from Intelsat. The solar array deployment system is the same simple spring-actuated system used on the OTS and Intelsat V spacecraft. The array components and the single items weighed mass values are shown in Fig. 10. In addition to the low mass, the ULP array has the

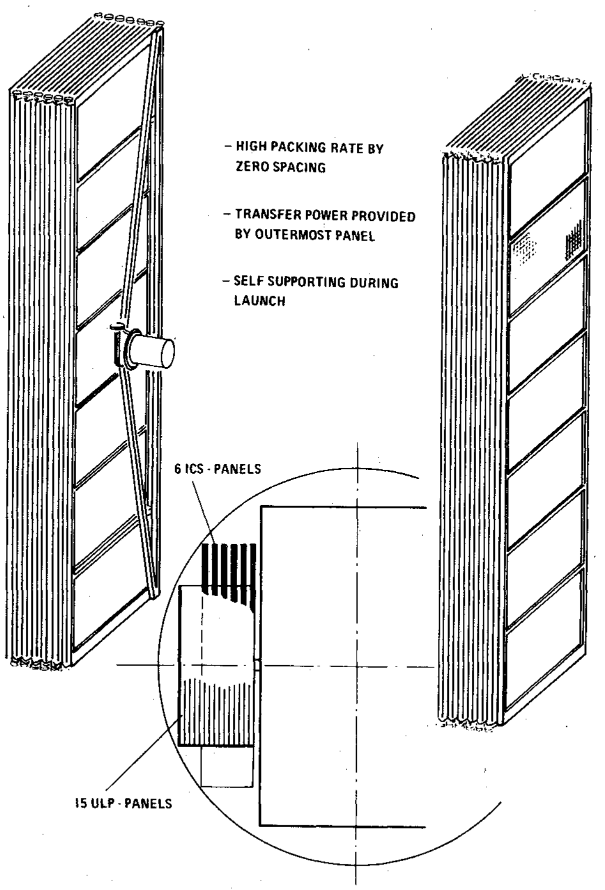


Fig. 11 ULP array stowage and packaging concept.

special advantage of high package density; the panels are stowed during launch directly onto each other with no space in between, as illustrated in Fig. 11. Conventional rigid panels need a 2 cm spacing for dynamic reasons. Compared to other flexible arrays (roll -out, fold-out), the ULP solution provides about 200 W power during the LEO to GEO transfer phase without any additional hardware or operational complication. These facts make the ULP array the preferred solution for high-power geosynchronous communication satellites. A technological improvement program has been started to use the new 50 µm solar cells on the ULP array in order to obtain a further mass reduction. The possible improvement is indicated in Fig. 9, resulting in another 28 kg saving for the already mentioned example of a 6 kW solar array.

The TV-SAT Concept

All the technology developments described in this paper have been performed over the past years with respect to the development of a TVBS for W. Germany. Consequently, the spacecraft concept derived in 1978/79 incorporates these technological features as shown in Figs. 12 and 13. Figure 12 shows the TV-SAT design which is organized in three modules: 1) CM—communication module with the transponder equipment and the antenna system; 2) SM—service module with the standard spacecraft subsystems; and 3) PM—propulsion module with the unified bipropellant system and the ion thruster assembly (Fig. 3). This modular design permits a separate integration and testing of the modules in parallel. Further, the adaptation of the spacecraft to other payloads is easily achieved.

The communication module uses a U-shaped structure as the most efficient solution, providing maximum area for equipment mounting and thermal control. The high-power (260 W) traveling wave tube collector heads are mounted externally so that free radiation is feasible from these parts with a temperature of about 300°C.

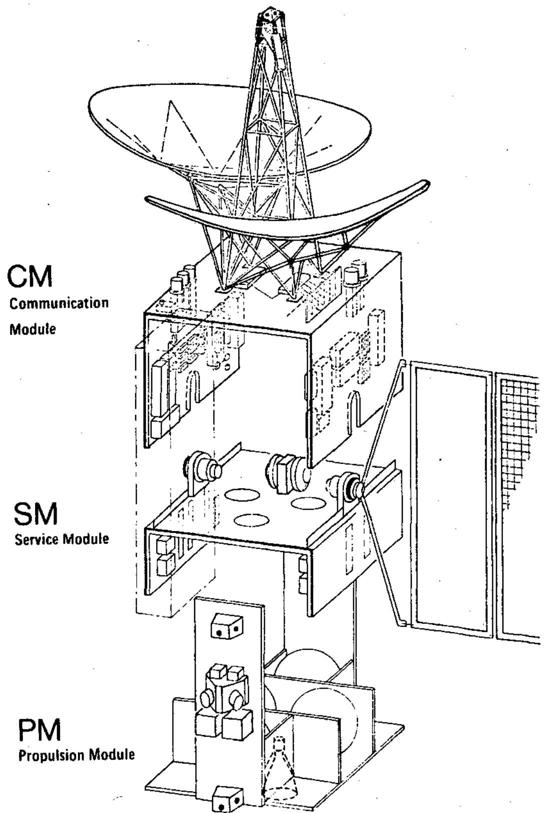
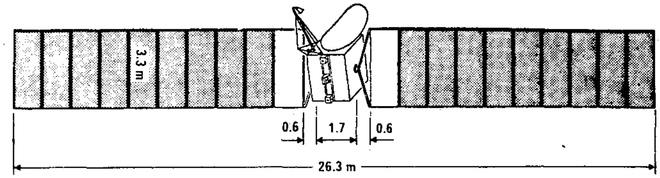


Fig. 12 TV-SAT modular design concept and components arrangement.

The main data of the operational TVBS for W. Germany with the designation TV-SAT A5 are summarized in Fig. 13. It is a typical design for a spacecraft employing new but qualified technology with a substantially increased performance. Cost analysis for the TV-SAT spacecraft and launches resulted in program cost reduction to one third, compared to a system using spacecraft with conventional technology and lower performance, requiring a larger number of S/C flight units and launches.

Conclusions

Direct TV broadcasting satellites require advanced technology in some areas in order to realize the performance



Mass in Transfer Orbit	1712 kg	Orbital Lifetime Bus	10 years
Mass at BOM	1020 kg	Payload	5 years
Propellant Mass - Biprops	54 kg	Reliability S/C Payload (5 y)	0.750
- Mercury	16 kg	Solar Array Power (BOM)	5.6 kW
Spacecraft Mass EOM	950 kg	Power EOM (10 y)	4.5 kW
Communication Payload	255 kg		

Fig. 13 TV-SAT A5 (operational version for W. Germany) data summary.

and cost-efficiency expected for this new type of communication service. The pre-development of such critical components has been performed in W. Germany during the past years with the result that the development of the first operational-type TVBS with five channels could be initiated by mid-1979. The examples described demonstrate how advanced technology can be used not only to achieve the required performance but also to improve the overall systems economy.

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