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# Evolution of the Intelsat System from Intelsat IV to Intelsat V

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**A brief introduction to the history of the Intelsat V program is given, and the communications subsystem characteristics are analyzed and compared with the corresponding characteristics of the previous Intelsat IV and IV-A series. The noise budget on the telephone channel is examined, taking into account the International Radio Consultative Committee (C.C.I.R.) recommendations and the Intelsat assumptions and emphasizing the derivation of the east-west and orthogonal polarization interference contributions. A typical noise budget of Intelsat V is compared with those of Intelsat IV and IV-A. The technologies employed in the various satellite subsystems together with mass and power budgets are reviewed, stressing the main difference between the technologies of Intelsat V and those of Intelsat IV and IV-A. Finally, the main characteristics of the launches of Intelsat V with Atlas-Centaur, Ariane, and the Space Shuttle are summarized.**

## Introduction

IN early 1973, at the same time that technical specifications were released for the Intelsat IV-A satellite, Intelsat started a system definition study on the following generation, the Intelsat V series, with a required operational availability by 1979.

Several configurations were subject to a preliminary investigation by Comsat, but only a few were studied in depth and submitted to the Board of Governors of Intelsat and to its Advisory Committee on Technical Matters. In particular, a satellite model with increased telecommunications capacity (resulting from the introduction of the 11/14-GHz frequency bands) compared with that of the Intelsat IV-A series was rejected because of its early saturation date on the Atlantic area (end 1981) and because of the requirement for an extensive introduction of traffic on the new 11/14-GHz frequencies.

Another model, relying only on the use of the traditional 4/6-GHz frequency bands and multibeam antennas with frequency reuse by spatial discrimination up to eight times on a 380-MHz bandwidth, and with an operational introduction expected around the end of 1980, was also discarded. This satellite model was also criticized for its reduced operational flexibility because the satellite configuration was tailored to a particular traffic situation and to a given earth station network (which are different for the three oceanic areas). Further, it was questionable whether the expected time schedule could be maintained because of the need to develop several new subsystems (multibeam antenna, static switching matrix, and solid state linear amplifiers).

Finally, at the eleventh meeting of the Intelsat Board of Governors (October 1974), the ultimate idea for the Intelsat V series was generated, stemming from the increased capability of the Atlas-Centaur. This improvement resulted from the launch trajectory optimization, which eliminated the radar tracking requirement from the NASA Ascension Island earth station, and the anticipated jettison of the nose fairings during the ignition of the Atlas stage.

The 57-kg increase in the geostationary orbit launch capability of the Atlas-Centaur could be utilized to increase the communications capacity in the 4/6-GHz frequency bands by introducing transponders on cross-polarized antenna beams, thereby illuminating the highest traffic areas. This concept allowed the technical specifications originally developed for the first model mentioned above, particularly for the 11/14-GHz payload, to remain essentially unchanged. More importantly, the extra capacity available in the 4/6-GHz bands allowed more time for gradual exploitation of the new 11/14-GHz frequency bands. Therefore, this concept was vigorously pursued beginning in July 1975.

## Communications Subsystem Characteristics[1]

Figure 1 shows the general configuration of the Intelsat V satellite in geostationary orbit, with the solar panels deployed. The antenna tower is oriented toward the Earth along the yaw axis, while the solar panels are deployed in the north-south direction along the pitch axis. The thruster clusters for attitude and stationkeeping control are mounted on the east and west panels around the roll axis.

Table 1† shows the main characteristics of the Intelsat V communications subsystem and compares them with the corresponding characteristics of the previous Intelsat IV (Ref. 2) and IV-A (Ref. 3) series. In particular, the following different characteristics should be noted.

### Antenna Subsystem and Interconnectivity Matrix

The antenna subsystem for the high directivity beams of increasing complexity evolves from the two-reflector configuration of Intelsat IV to three reflectors for Intelsat IV-A and four reflectors for Intelsat V.

The four reflectors of Intelsat V are all of the circular aperture type; two operate at 11/14-GHz, one at 6 GHz, and one at 4 GHz. Each reflector at 11/14 GHz is of the offset illumination geometry, realized by a corrugated conical horn with linear orthogonal polarizations at 11 GHz and 14 GHz. The west spot reflector is parabolic in both the vertical and

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†In January 1979, Intelsat exercised an option to add a global L-band capability to the basic spacecraft to provide maritime ship-to-shore communications. This option, which starts with flight 5, adds hardware and bandwidth which are not reflected in this or subsequent tables.

**Table 1 Main characteristics of the communication subsystems of Intelsat IV, IV-A, and V satellites**

| Characteristics | Intelsat IV | Intelsat IV-A | Intelsat V |
|---|---|---|---|
| Antenna coverages | Global at 4/6GHz<br>No. 2 4.5 deg spot beams completely steerable at 4 GHz | Global at 4/6GHz<br>No.2 east and west hemispheric beams at 6 GHz<br>No. 2 east and west hemispheric beams re configurable to 4 zone beams at 4 GHz | Global at 4/6 GHz<br>No. 2 east and west hemispheric beams at 4/6 GHz<br>No. 2 east and west zone beams on opposite polarization at 4/6 GHz<br>No. 2 steerable spot beams at 11/14 GHz, one 1.6 deg circular, one 1.8 × 3.2 deg elliptical |
| Frequency reuse | No | By spatial discrimination | By spatial discrimination at 4/6 GHz and 11/14 GHz<br>By polarization discrimination at 4/6 GHz |
| Maximum/(minimum) useful bandwidth, MHz | 432 (432) | 720 (628) | 2137 (1885) |
| Total number of TWTA's | 24 | 32 | 43 |
| Maximum/(minimum) number of active transponders | 12 (12) | 20 (18) | 27 (25)[a] |
| Maximum useful rf power, W | 72 | 104 | 198.5 |
| Number of active receivers (and total) | 1 (4) | 3 (6) | 7 (15) |
| G/T,[g] dB/K | | | |
| Global | −18.6 | −18.6 | −18.6 |
| Hemispheric | ... | −11.6 | −11.6 |
| Zone | ... | ... | −8.6 |
| Spot | ... | ... | East 0; West +3.3 |
| Sat. flux,[d] dBW/m² | | | |
| Global | −73 | −75 | −75[b] |
| Hemispheric | ... | −75 | −72[c] |
| Zone | ... | −75 | −72 |
| Spot | −66 | ... | East −77; West −80.3 |
| EIRP,[g] dBW | | | |
| Global | 22 | 22 | 23.5[e] |
| Hemispheric | ... | 26 | 29[f] |
| Zone | ... | 29 | 29 |
| Spot | 33.7 | ... | East 41.1; West 44.4 |
| Atlantic primary configured capacity in FM/FDMA (telephone circuits) | 4300 + 2 TV | 6800 + 2 TV | 13,400 + 2 TV |

[a] The number of active tubes is always 27 because two tubes operate in parallel.
[b] −72 dBW/m² for channel (7-8).
[c] −75 dBW/m² for channel (9).
[d] These values represent the saturation flux for single carrier operation; in multicarrier operation, the saturation flux is higher and the transponder gain is lower.
[e] 26.5 dBW for channel (7-8).
[f] 26 dBW for channel (9).
[g] These values are the specification values. The average measured values or those expected in orbit are generally 0.5 dBW higher for the effective isotropic radiated power (EIRP) and improved by 1 dB/K for the gain-to-noise temperature ratio (G/T).

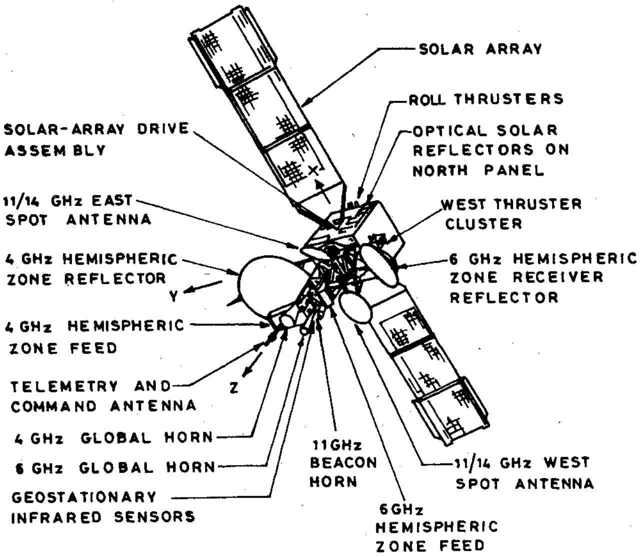


Fig. 1 Intelsat V configuration.

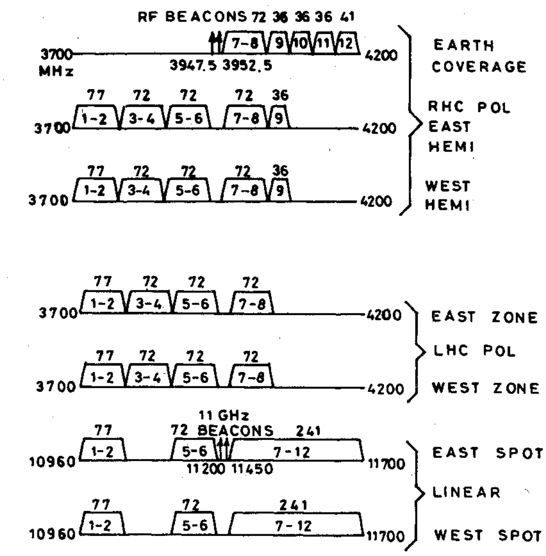


Fig. 2 Intelsat V transmit frequency plan.

horizontal planes to produce circular 1.6 deg antenna beams, while the east spot reflector is parabolic in the vertical plane but shaped in the horizontal plane to produce elliptical beams. The two reflectors at 4 GHz and 6 GHz are also of the offset-fed type; however, the feed system is much more complex because of the need to generate highly shaped hemispheric and zone beams (with opposite senses of circular polarization).[4,5]

Each feed array, at 4 GHz and 6 GHz, is composed of 88 square waveguide feed horns (compared with the 37 and 19 feed elements of Intelsat IV-A, for odd and even channels, respectively) excited with proper amplitude and phase through power division/phasing networks. Unlike the previous Intelsat IV and IV-A satellite configurations, the even and odd channels are collocated on a common waveguide manifold and then connected to a single 4-GHz antenna, instead of two separate antennas. This was made possible by an advanced contiguous design of the output multiplexer.

On Intelsat V, the interconnectivity matrix is very complex because, in addition to the transponder switching capability between global and hemispheric coverage, there are various cross-strapping combinations between hemispheric and zone beams, hemispheric and spot, and spot and zone beams. Moreover, Intelsat V transponders have several different bandwidths, as shown in the transponder plan of Fig. 2 (see Ref. 4). Table 2 summarizes the various bandwidths available for the different operational modes. The selected configuration is (will be) the best compromise between the mass constraints and the analysis of traffic requirements until the mid-1980s.

In the 11/14-GHz frequency band, not all of the 500-MHz bandwidth available on the basis of the International Radio Regulations is utilized, but the lower half is partially channelized into two 80-MHz transponders, without using the

Table 2 Available bandwidths in the various Intelsat V operational modes

| Operational mode | Maximum/(minimum) bandwidth, MHz |
|---|---|
| Direct inter- or intra-spot | 780 (338) |
| Direct inter- or intra-hemispheric | 658 (144) |
| Direct inter- or intra-zone | 586 (154) |
| Direct intra-global | 221 (113) |
| Cross-strap Hemi -spot [(1-2), (5-6)] | 298 (0) |
| Cross-strap Hemi -zone [(3-4), (5-6)] | 288 (0) |
| Cross-strap zone spot (7-8) | 144 (0) |

intermediate channel (3-4). This has allowed a mass reduction of about 30 kg compared with a full three-transponder channelization, with no impact on the satellite saturation capacity, considering the relatively low traffic foreseen at 11/14 GHz. Moreover, such a configuration is particularly useful if different Frequency Division Multiple Access (FDMA) and Time Division Multiple Access (TDMA) carriers should coexist on the same satellite. In such a case, channels (1-2) and (5-6) could be used with single-carrier four-phase PCM/PSK in a 120 Mbit/s TDMA system, cross-strapped with the hemispheric beam transponders, while channel (7-12) can be used with normal FDMA carriers.

Additional channelization of channel (7-12) at 11 GHz in two channels [(7-8) and (9-12)] would have offered greater flexibility, allowing direct inter-spot traffic in channel (9-12), even when channel (7-8) is used in this cross-strapped mode between spot and zone beam transponders. However, the implied mass increase did not allow such an implementation.

Also, the selected channelization of the hemispheric and zone beam transponders, with a gross bandwidth of 80 MHz, was the best compromise between the mass limits and the overall capacity, considering the increased useful bandwidth loss for the guardbands with higher channelizations.

#### Transponder Design

The maximum number of active transponders has increased from 12 for Intelsat IV to 20 for Intelsat IV-A, and to 27 for Intelsat V. Correspondingly, the maximum useful output power from the final amplifiers has increased from 72 W for Intelsat IV [(12 traveling wave tube amplifiers (TWTA's), 6 W each] to 104 W for Intelsat IV-A (16 TWTA's, 5 W each for the hemispheric transponders; and 4 TWTA's, 6 W each for the global transponders), and to 198.5 W for Intelsat V [6 TWTA's, 10 W each at 11 GHz; 11 TWTA's, 8.5 W each for the hemispheric and global transponders; and 10 TWTA's, 4.5 W each for the zone transponder and for the two hemispheric transponders ].

The overall number of redundant elements for the TWTA and the receivers has also increased; however, the higher degree of complexity for the communications subsystems together with the mass constraint has required a more judicious use of redundancies. Therefore, in terms of the final amplifiers, the $2\times1$ configuration of Intelsat IV (two TWTA's available for each active TWTA) has evolved into the $3\times2$ configuration for the hemispheric transponders of Intelsat IV-A. The $3\times2$ configuration is also used for all the Intelsat V transponders, except for the two transponders of the upper half of the 11 GHz-band and global transponders

10, 11, and 12 for which the 2×1 configuration has been retained. Relative to the receivers, the 4×1 configuration of Intelsat IV has been replaced by 4×2 and 2×1 configurations, but with some redundant elements technologically different for the hemispheric and global receivers of Intelsat IV-4, respectively. Intelsat V has seven receivers simultaneously active, with a 4×2 configuration on the spot, hemispheric, and zone beams, and a 3×1 configuration on the global beam.

With reference to the gain steps on the various transponders, Intelsat V has a configuration similar to that of Intelsat IV-A, with a 7.5-dB gain step for the 6/4-GHz transponders. Therefore, each 4-GHz transponder has preceding the final TWTA a ground-commandable attenuator which is inserted in the multicarrier operational mode to operate with a lower transponder gain. That is, a higher saturation flux density transmitted from the ground higher values of the carrier-to-noise ratio (C/N) in the up-link $(C/N)_u$ to compensate for the higher intermodulation noise.

It is possible to insert a 5-dB gain step into the 11-GHz transponders of Intelsat V, and to command from the ground the insertion of a 7.5-dB attenuator into the 6-GHz receivers. This allows a corresponding gain step on the overall 6-GHz bandwidth for each group of transponders on the global, hemispheric, and zone beams. This would permit efficient operation of a satellite (or part of it) intensively used by small earth stations, and would also protect against possible receiver gain loss similar to that experienced on Intelsat IV.

## Analysis of the Noise Budget on the Telephone Channel

The distribution of the 7500-pWp (picowatts psophometric) space segment noise[6] among the various contributions differs, depending on the technical characteristics of the specific satellite generation. Table 3 shows distribution variations for typical telephone carriers operating similarly on the three satellite generations Intelsat IV, IV-A, and V.

Therefore, consideration has been given to carriers operating on transponders connected to the spot beams of Intelsat IV vs carriers operating on the inter-zone transponders of Intelsat IV-A and on inter-hemispheric transponders of Intelsat V. The values shown in Table 3 have been derived according to the following considerations. The specific carrier-to-noise ratios for the up-link, the down-link, and intermodulation have been determined by computer using appropriate values for the fixed satellite and earth station characteristics [e.g., single-carrier saturation flux density, gain-to-noise temperature ratio of the satellite and earth station, and effective isotropic radiative power (EIRP) of the saturated satellite TWT]. The values shown for Intelsat IV and IV-A have been derived from Refs. 3 and 7, respectively. The values for Intelsat V have been extracted from appropriate documentation submitted to the Intelsat Advisory Committee on Technical Matters. The C/N values, representing the interference from transponders reusing the same frequency bands by spatial discrimination (east-west) or polarization discrimination, are based on the isolation performance of the satellite antennas. The 24 dB of C/N for the east/west co-channel interference of Intelsat IV-A is derived from the power combination of the two C/N values of 27 dB, referred to the isolation specifications, which are separately applicable to the up- and down-link between one main beam (e.g., east) and the interfacing sidelobe of the other beam (e.g., west).

For Intelsat V, the calculation is complicated by an additional interference source attributable to frequency reuse by polarization discrimination; hence, it is also necessary to consider the polarization isolation performance of the earth stations. In addition, Intelsat V uses the frequency interleaving carriers planning technique extensively to limit co-channel interference. The advantage of this technique must be properly assessed and quantified. Therefore, for example, the C/N value of 22.2 dB for the east-west co-channel interference has been calculated with the following procedure: the up-link and down-link contributions have been separately calculated; each has been derived from the combination of the two contributions, due to interference from co-polarization and cross-polarization channels (but always irradiated from a spatially discriminated beam).

These last contributions have been derived based on the fundamental hypothesis relative to the isolation performance of the satellite antennas and the evaluation of the advantage of the frequency interleaving technique. Table 4 summarizes this procedure and the assumed values for the various C/N's. The 27-dB value reflects the isolation specifications among the various beams of Intelsat V and indicates that each desired carrier is subject to interference from two interfering adjacent co-polarization carriers and from two cross-polarization carriers because of the frequency interleaving configuration.

Moreover, the frequency interleaving advantage, estimated to be 2.5 dB and 7 dB for the co-polarization and cross-polarization carriers, respectively, and applicable to each interfering carrier, has been verified both analytically and by laboratory measurements. The justification for the different values of the frequency interleaving advantage is that, for maximum utilization of such a technique, particularly for the carriers which rely only on polarization isolation that degrades in severe weather conditions, it is unavoidable that the co-polarization carriers with spatial isolation discrimination will be co-frequency or almost co-frequency. It has been assumed that the various interference entries add on a power basis.

The procedure for deriving the 22.9-dB C/N shown in Table 4 for co-channel interference due to cross-polarization in clear weather conditions can be examined. Table 5 shows the details of partial C/N values. This case must consider that the polarization isolation performance of the earth station antennas is specified as 30 dB (axial ratio 1.06), and that the combination of earth station signal isolation and satellite isolation is a voltage ratio combination.

In adverse weather conditions, for 0.01% of the year, rain will cause the polarization isolation of the earth stations to drop as low as 15 dB. In this case, it is reasonable to assume

**Table 3 Space segment typical noise budget for Intelsat IV, IV-A, and V[a]**

| Noise source | Intelsat IV (Spot) C/N, dB | N, pWp | Intelsat IV-A (Zone) C/N, dB | N, pWp | Intelsat V (Inter-hemispheric) C/N, dB | N, pWp |
|---|---|---|---|---|---|---|
| Up-link thermal | 23.7 | 3270 | 25.4 | 1030 | 27.4 | 370 |
| Down-link thermal | 27.3 | 1430 | 20.1 | 3460 | 18.3 | 3050 |
| Intermodulation | 24.3 | 2800 | 23.5 | 1590 | 20.6 | 1800 |
| Co-channel east-west interference | ... | ... | 24.0 | 1420 | 22.2 | 1240 |
| Co-channel cross-polarization interference | ... | ... | ... | ... | 22.9 | 1040 |
| Total | 20.1 | 7500 | 16.8 | 7500 | 14.4 | 7500 |

[a] Valid only in nominal clear sky conditions.

**Table 4 Intelsat V east-west co-channel interference budget**

| East-west co-channel interference | Up-link C/N, dB | Down-link C/N, dB |
|---|---|---|
| Co-polarization isolation, interfering carriers 1 and 2 | 27 | 27 |
| Frequency interleaving advantage | 2.5 | 2.5 |
| Net co-polarization isolation | 26,5 | 26,5 |
| Orthogonal polarization isolation, interfering carriers 3 and 4 | 27 | 27 |
| Frequency interleaving advantage | 7 | 7 |
| Net orthogonal polarization isolation | 31,0 | 31,0 |
| Co-channel interference on each link | 25.2 | 25.2 |
| Total co-channel interference | 22.2 | |

**Table 5 Intelsat V orthogonal polarization interference budget**

| Orthogonal polarization co-channel interference | Up-link C/N, dB | Down-link C/N, dB |
|---|---|---|
| Earth station polarization isolation | 30 | 30 |
| Satellite antenna polarization isolation | 27 | 27 |
| Interfering signal net isolation | 22.4 | 22.4 |
| Frequency interleaving advantage | 6.5 | 6.5 |
| Orthogonal polarization isolation, interfering carriers 1 and 2 | 28.9 | 28.9 |
| Co-channel interference on each link | 25.9 | 25.9 |
| Total co-channel interference | 22.9 | |

that, on the up-link, the interleaved flanking carriers on the opposite polarization are transmitted from different earth stations and that, consequently, the isolation of only one flanking carrier is degraded. On the down-link, both the interfering carriers are subject to a signal isolation degradation, which is also assumed to be 15 dB. Although the 6-GHz depolarization is higher than that at 4 GHz, the fact that the up-link interference is also attenuated must be considered. On the down-link, both the depolarized interferers and the desired carriers are equally attenuated. With calculations similar to those in Table 5, it is possible to calculate the degraded C/N for 0.01% of the year, due to co-channel interference for rain depolarization, which is 18.3 dB.

When the partial C/N values given in Table 3 for the up-link and down-link thermal noise have been determined, assuming the noise bandwidth as the total useful bandwidth of a transponder, the total C/N has been calculated. Then, it is always possible to establish a correspondence between the total C/N and the total noise budget for the space segment (7500 pWp) by a proper choice of the noise bandwidth and, therefore, of the modulation index of the various carriers. Finally, the noise in pWp corresponding to each partial C/N can be calculated from the difference between the total C/N and the partial C/N. For example, the comparison of the 18.3-dB value of C/N for the co-channel interference due to rain depolarization for 0.01% of the year with the 22.9-dB value of C/N in clear weather (see Table 5), corresponding to 1040 pWp noise, makes it easy to calculate a noise figure of about 3000 pWp in degraded weather conditions.

Table 3 shows that during the transition from Intelsat IV to Intelsat IV-A and to Intelsat V, it has been necessary to reduce the sum of the noise contributions due to the up-link, the down-link, thermal noise, and intermodulation noise to allow the allocation of noise contributions for interference due to the frequency reuse techniques. Therefore, the trend, which is expected to accelerate, is from satellites limited by thermal noise to interference-limited satellites.

The up-link thermal noise reduction from Intelsat IV to IV-A is justified by the improved satellite gain-to-noise temperature ratio (G/T); the additional reduction of this contribution on Intelsat V is due to the higher saturation flux density and to the decreased incidence of the up-link C/N relative to the total C/N. The down-link thermal noise is lower for Intelsat IV, due to the higher EIRP of its spot beams, while the minor differences between Intelsat IV-A and V are mainly due to the fact that the output back-off of the satellite TWTA is slightly higher for Intelsat IV-A. This reflects on the intermodulation noise, which is slightly higher for Intelsat V than for Intelsat IV-A; for Intelsat IV, this contribution is higher even with a higher back-off because of the higher incidence relative to the total C/N.

## Communications Subsystem Technologies[4,5]

The new communications technologies introduced on Intelsat V are mainly intended to limit the overall mass of the communications subsystem. Despite the increase in the complexity of Intelsat V, the mass of the communications antennas is approximately unchanged (about 63 kg), while the mass of the transponder has increased about 45 kg (from 124 to 169 kg), which is not excessive considering the increased number of transponders and their more complex configuration. These achievements have been possible due to the introduction of the following technologies: 1) lightweight materials of the graphite fiber-reinforced plastic (GFRP) type for the 4/6-GHz feed, the antenna tower structure, waveguides, and input and output multiplexers at 4/6 GHz; 2) 4-GHz output multiplexers of an advanced contiguous design, which permit the use of single transmit antennas rather than duplicate odd and even antennas; and 3) receivers with all solid-state components and microwave integrated circuits (MIC's).

Special attention has been given to the reliability aspects of these technologies as well as to those of the other new technologies incorporated into the Intelsat V design. For example:

1) The extensive long-term dimensional stability tests performed on cavities and filters manufactured with GFRP materials to insure a maximum shift of the central frequency of the filters not exceeding ±360 kHz for aging effects (ten-year lifetime) and ±125 kHz for temperature variations of 70°C. It was necessary to perform an in-depth investigation of the fabrication techniques, residual moisture effects, and auto-compensation of the tuning screws.

2) The conservative selection of the receiver components both at 6 and 14 GHz, which led to the choice of four-stage bipolar transistor amplifiers at 6 GHz and tunnel diode amplifiers at 14 GHz because of their lesser long-term instability risk compared with the FET devices, although the latter yield somewhat higher performances. As a result of additional work in this area, FET devices are now scheduled to be incorporated in the 6-GHz receivers beginning with flight 5. The extensive investigation of the fabrication methods for the MIC with alumina or fused silica substrates, through Intelsat contracts, research and developments to improve reliability and reproducibility.[8] The use of accurate screening techniques, based on COMSAT Laboratories' developments,[9] for the tunnel diodes to be used in the flight units.

Table 6 Mass budgets (in kg) of Intelsat IV-A and Intelsat V

| Subsystem | Intelsat IV-A (F-1) | Intelsat V[a] |
|---|---|---|
| Communications antenna | 63 | 67.4 |
| Communications transponders | 124 | 167.1 |
| Telemetry and command | 25.4 | 25.8 |
| Electrical power[b] | 93.3 | 143.9 |
| Attitude control | 64.5 | 70.2 |
| Propulsion | 57.5 | 38.1 |
| Structure and apogee motor[b] | 219.1 | 256.1 |
| Electrical integration | 24.2 | 40.5 |
| Dry mass | 671 | 809.1 |
| Hydrazine | 158 | 190.5 |
| In-orbit mass | 829 | 999.6 |
| Apogee motor fuel | 652.8 | 870.6 |
| Adapter | 34.3 | 18.7 |
| Launch mass | 1516.1 | 1888.9 |

[a] Approximate values, estimated in March 1979, and valid for Atlas-Centaur launches. For STS or Ariane launches, some variations in the apogee motor fuel and in the hydrazine mass are expected as a consequence of the different transfer orbit characteristics (see Table 8).
[b] The solar array substrate mass (about 35 kg in both cases) is included as part of the structure for Intelsat IV-A and as part of the electrical power subsystem for Intelsat V.

Table 7 Power budgets (in W) of Intelsat IV-A and Intelsat V

| Subsystem | Intelsat IV-A | Intelsat V |
|---|---|---|
| Communications | 414 | 772.4 |
| Electrical power | 0.5 | 9.1 |
| Telemetry and command | 16.6 | 39.2 |
| Attitude control | 28.4 | 47.7[a] |
| Thermal control | 11.1 | 112.3[a] |
| $I^2R$ harness losses | ... | 9.8 |
| Propulsion | 0.3 | 0.8 |
| Total battery load | 470.9 | 991.3 |
| End-of-life battery charging[a] | 54.8 | 100.7 |
| Total solar panels load | 525.7 | 1092 |

[a] Autumnal equinox values indicate the most severe condition because the reduced power load of the attitude control subsystem is exceeded by the higher power load of the thermal control subsystem.

3) The extensive analysis of the behavior of the 10 W TWT's at 11 GHz, derived from the 20-W dual collector TWT developed for the European satellite OTS to insure a seven-year lifetime, has focused mainly on the cathode current degradation mechanisms with time. These tubes are equipped, for the first time on a commercial satellite program, with impregnated cathodes which, unlike the oxide cathode, have a higher cathode current density (about 0.8 $A/cm^2$ against 0.2 $A/cm^2$), with the advantage of a lower convergence of the electron beam between cathode and helix for a higher emission stability during the life of the tube.[10]

## Technologies of Subsystems Other than Communications[4,5]

### Mass and Power Budgets

It is interesting to compare the mass and power budgets for the various subsystems of Intelsat V and Intelsat IV-A (see Tables 6 and 7). The justification for the most significant discrepancies is briefly discussed in the following subsections.

### Attitude Control Subsystem

Intelsat V is the first generation of Intelsat satellites with three-axis stabilization in geostationary orbit. Such a stabilization design is derived from one successfully used experimentally on the French-German Symphonie satellites, based on the use of a fixed momentum wheel for the active control of the pitch axis.

The design also includes a redundant wheel with rotational axis parallel to that of the first wheel, which can be activated by ground command if needed.

Unlike the Symphonie satellites, Intelsat V has active control of the roll axis in the normal mode of operation, which is realized in a closed loop utilizing the error signals from the geostationary infrared sensors. This constrains the spacecraft motion to a small angle limit cycle, instead of having a less accurate open-loop system via the telemetry and command earth stations.

Intelsat V is also provided with closed-loop control of the yaw axis utilized, in addition to pitch and roll control during corrections for north-south or east-west stationkeeping. Spin-stabilized satellites such as Intelsat IV/IV-A are drum spinners with large values of angular momentum, such that the spin axis attitude can be corrected by ground command, without the need for direct yaw sensing during the stationkeeping maneuvers. In contrast, attitude control subsystems that depend on bias momentum wheels (e.g., Intelsat V) require active yaw control during stationkeeping to maintain accurate pointing. The current design practice is to size the momentum wheel for the background disturbance torque caused by unbalanced solar pressure, which is typically three orders of magnitude smaller than the thruster disturbance torques that arise during stationkeeping. Therefore, a yaw thruster control loop with a yaw sensor is necessary. For Intelsat V, it is a wide-angle high-accuracy digital sun sensor.

The east-west and north-south stationkeeping maneuvers cannot be performed during periods of low sensitivity to the yaw angle—that is, around the local noon or midnight, relative to the subsatellite point. With the wide angle sun sensor developed for Intelsat V, the velocity must be within $\pm 59$ deg of the sun line.

With the devices described above, the expected pointing accuracy ($3\sigma$ value) is $\pm 0.12$ deg on the roll and pitch axes and $\pm 0.33$ deg on the yaw axis to satisfy the coverage requirements defined by the list of earth stations to be served under the worst case pointing error. For comparison, the $3\sigma$ pointing accuracy for the Symphonie satellites was $\pm 0.5$ deg in the normal mode of operation and $\pm 1$ deg during the stationkeeping maneuvers, for all axes.

Another unique characteristic of the Intelsat V attitude control subsystem is the incorporation of a magnetic roll torque compensation scheme using a dipole aligned with the spacecraft yaw axis to interact with the earth magnetic field. With such a system it is possible to reduce the unbalanced solar pressure disturbance torque, consequently reducing the total number of daily thruster fairings around the roll axis from about 200 to about 17 during the solstices. In terms of the mass budget, no saving is realized since the mass of the magnetic torquer coils and associated control circuits is approximately equal to the mass saving in hydrazine.

Furthermore, despite its three-axis stabilization system in geostationary orbit, Intelsat V needs a spin-stabilization system during the transfer orbits to average out the misalignments between the thrust direction of the solid propellant apogee motor and the center of mass of the spacecraft. Therefore, the satellite is equipped with spin-up thrusters to provide the necessary rotational speed at the separation from the launcher, when the launch vehicle is an Atlas-Centaur or an Ariane with a third stage that is essentially three-axis stabilized. After the spin-up command sequence, which lasts about 9 min, an automatic nutation control device is activated to maintain the nutation half-cone angle at less than 0.1 deg. After the apogee motor firing and the completion of the velocity correction maneuver in the drift orbit, the spin angular velocity is removed to switch to the body stabilization mode.

Tables 6 and 7 confirm the higher complexity of the attitude control subsystem of Intelsat V compared to Intelsat IV-A, with larger mass and power consumption. It should be noted that the power consumption of 47.7 W quoted in Table 7 for

Intelsat V is a minimum value valid at the autumnal equinox; the maximum value (about 73 W) is expected at the solstices when the solar torque is higher; and, therefore, the current required by the magnetic torquer is also higher.

#### Propulsion Subsystem

The most important new technology introduced in the propulsion subsystem of Intelsat V is the incorporation of four electrothermal thrusters (two operational and two spare) to reduce the hydrazine mass required. This requirement is significantly larger than that of Intelsat IV-A due to the larger overall mass of the spacecraft (see Table 6) and to the larger velocity correction value required during the useful lifetime.

The required $\Delta V$ is 464.1 m/s for the Intelsat V launches with Atlas-Centaur compared with the 428.7 m/s required for Intelsat IV-A. The difference is mainly attributable to a more conservative assumption about the effect of the lunar perturbation cycle on the orbital plane inclination drift during the life of Intelsat V. The electrothermal thrusters are used for the north-south control of the satellite, which requires the largest portion of propellant. Such thrusters can deliver a mission average specific impulse of about 290 s by heating hydrazine propellant to about 2200 K prior to ejection. The mass saving of hydrazine, for a useful life of seven years, is on the order of 20 kg, compared to the use of catalytic hydrazine thrusters which deliver a specific impulse of about 230 s (Ref. 4).

The overall number of thrusters is 20 (with thrust ranging from 22.2 N for the initial orbit correction maneuvers to 0.3 N for the electrothermal thrusters) and is divided into two sets of 10 thrusters; each set can be fed by any one of two titanium propellant tanks. The system with two propellant tanks has been preferred to the four-tank system originally proposed because of its simplicity (less plumbing and isolation valves), even if the four-tank configuration would offer better mass balance in case of failure of one-half of the system. The overall mass of the propulsion subsystem of Intelsat V is lower than that of Intelsat IV-A (which has four hydrazine tanks) despite the fact that Intelsat IV-A has only six 26-N catalytic thrusters. With reference to power consumption, there is no significant difference because the current needed for the electrothermal thruster heaters (15 A) is received from the batteries through a separate bus; obviously, the electrothermal thrusters cannot be fired during the eclipse periods.

#### Electrical Power Subsystem

Similar to that of the previous Intelsat satellite generations, the power supply subsystem is based on the use of N-P silicon solar cells and nickel-cadmium rechargeable batteries for the eclipse periods. The essential configuration of the electrical power subsystem is conceptually similar to that of Intelsat III. That is, bus voltage from the two solar array panels is regulated with sequential linear partial shunt regulators which provide a bus voltage of 42 $\pm 0.5$ V (compared with the unregulated 24.5 V of Intelsat IV and IV-A, and with the 29 $\pm$ 2 V of Intelsat III).

The higher bus voltage has the advantage that, for the same power, the current is lower with a consequent reduction in the mass of cables and current switching elements, even if higher values for the switching transistor voltage ratings and capacitor voltage ratings are required. The regulation of the bus voltage by regulators on the solar array wings avoids the large voltage variations which would otherwise occur according to the temperature variations of the solar cells at eclipse exit. The lower solar cell temperatures at eclipse exit cause an increase of the bus voltage from 24.5 to 48 V, with a transient of several minutes, on the Intelsat IV/IV-A satellites; this represents a severe penalty to the load regulator design. Without the array shunt regulators, the situation would have been even more severe for Intelsat V, due to the higher value of the bus voltage and to the higher temperature excursions experienced by body-stabilized satellites compared to spin-stabilized satellites.

The battery technology is very similar to that of Intelsat IV-A. The configuration of Intelsat V is based on two batteries which provide a minimum voltage of 27 V (with a single-battery cell failure) and have a capacity of 34 A·h and a mass of 32 kg (compared with 23.8 V, 18 A·h, and 19.5 kg for the Intelsat IV batteries). Therefore, the total bus voltage excursion is from 27 to 42.5 V.

The maximum specified depth of discharge of the batteries is 55%, as for Intelsat IV-A. The solar panel technology of Intelsat V (derived from the technology developed for the European OTS satellite) represents a significant advance compared to the previous Intelsat satellites. Although the solar cells are of the K 4 type, with 11.2% efficiency, already used on Intelsat IV-A, there has been a significant improvement in the power-to-mass ratio at the end of life allowed by the three-axis stabilization and by the sun-oriented planar solar array wings. The latter are realized with a lightweight rigid mechanical structure fabricated from woven graphite face sheets bonded to an aluminum honeycomb core. The minimum end-of-life power-to-mass ratio at summer solstice for the Intelsat V solar panels is about 20 W/kg (1,288 W and 65 kg) as compared with 6.9 W/kg for Intelsat IV-A and 6.2 W/kg for Intelsat IV. Therefore, the end-of-life power subsystem is 9 W/kg for Intelsat V vs ~4 W/kg for Intelsat IV/IV-A.

#### Telemetry, Command, and Ranging Subsystem

Similar to the previous Intelsat satellite generations, the telemetry is performed by modulating the 4-GHz beacons, and the commands are transmitted in the 6-GHz band—both in transfer orbit and in the geostationary orbit. The ranging measurements are also performed in the 6- and 4-GHz bands, with the multiple tone system.[11] However, unlike the previous satellite generations, three tones are transmitted instead of four. (The lowest frequency tone has been eliminated because it only provides knowledge of the distance of the satellite from the TT&C station with less ambiguity.) On Intelsat V, the ranging is performed by properly converting the command carrier to the telemetry carrier frequency. Therefore, the ranging measurements are completely independent of the communications traffic, and it is easier to perform the ranging during the transfer orbit because the signals are routed through the telemetry and command antennas with toroidal beams rather than through the communication antennas. On Intelsat IV/IV-A it was necessary to use a common communications carrier, e.g., the TV carrier. Obviously, Intelsat V does not require simultaneous ranging and command operations.

#### Thermal Control Subsystem

The thermal control subsystem of Intelsat V is conceptually similar to that of the previous Intelsat satellite generations; therefore, it is accomplished using conventional passive techniques including selective location of power-dissipating components, multilayer insulation surface finishes, optical solar reflectors, and heaters. However, since Intelsat V is three-axis stabilized, the design of the thermal control subsystem is more complex than that of the previous spin-stabilized satellites, which were subject to generally lower thermal gradients.

#### Apogee Motor and Launchers

The launch schedule of Intelsat V flight units projects three launches by the end of 1980 and four launches in 1981 or later. This schedule coincides with the transition period envisaged by NASA, from the utilization of expendable launchers to the exclusive use of the Space Transportation System (STS). Therefore, the satellites must be designed to be compatible with launches by the Atlas-Centaur expendable

Table 8 Intelsat V launch characteristics

| Characteristic | Atlas-Centaur | Ariane | STS/SSUS-A |
|---|---|---|---|
| Transfer orbit inclination, deg | 27.7 | 8.5 | 24.3 |
| Spin-up | Yes | Yes | No |
| Apogee motor fuel, kg | 87.4 | 69.7 | 871.4 |
| Apogee motor dispersion correction hydrazine, kg | 39.2 | 26.2 | 43.5 |

launch vehicles for the first four flight units and by the Space Shuttle (Orbiter plus SSUS-A) for one or two of the remaining three units.

In addition, Intelsat has specified the compatibility of the last three units of Intelsat V with the Ariane launcher of the European Space Agency (ESA) because this new launch vehicle is economically competitive with the STS and because of the lack of historic data on the reliability of the two launching systems. Intelsat is also committed to launch one of the two last flight units of Intelsat V on Ariane. This threefold compatibility with different launchers has been achieved by using the same apogee motor, with a reduced propellant load for Ariane which takes advantage of a quasiequatorial launching base. A detailed analysis of the vibration environment (levels and frequencies of the flight mechanical oscillations) has been performed. This environment is more severe for Ariane, in terms of the sinusoidal vibrations.[12]

With reference to the thermal control requirements during the launch, there are significant differences between the STS and expendable launch vehicles because of the power dissipation of the Orbiter and the spacecraft heating or cooling while in the Orbiter bay. This is attributable to directly incident solar energy and solar energy reflected from the Shuttle and other payloads during the period of flight with Orbiter doors open, which may last several hours.

However, since the thermal environment was under definition at the time of the contract signature for the Intelsat V satellites, the contractor was required to design the spacecraft to withstand all the thermal environments applicable to the entire mission when launched by the Atlas-Centaur. The requirements to maintain adequate Intelsat V spacecraft temperature during the Shuttle launch phase therefore devolve on the design of Shuttle hardware and mission operations. However, it was required that the spacecraft contractor perform thermal analyses and support interface activities to establish the thermal requirements for launching the spacecraft with the Shuttle.[13] Table 8 summarizes the main characteristics of Intelsat V launches with the three types of launchers.

## Concluding Remarks

The Intelsat V generation of satellites described in this paper represents a significant step in the evolution of the Intelsat space segment. The most important new features of this series can be summarized as follows:

1) It is the first Intelsat series to introduce the operational use of the 11/14-GHz frequency bands and of the frequency reuse by polarization discrimination in the 4/6-GHz bands.

2) It is the first Intelsat series with three-axis stabilization in geostationary orbit.

3) It is the first Intelsat series of multipurpose satellites, i.e., for fixed satellite service as well as for maritime ship-to-shore communications, starting with flight 5.

4) It is the first Intelsat series to be compatible with different launchers: the expendable Atlas-Centaur, provided by NASA; Ariane, provided by ESA; and the NASA Space Transportation System.

5) It is the first Intelsat series which incorporates several new advanced technologies such as GFRP multiplexers, dual-collector impregnated-cathode TWT's at 11 GHz, electrothermal thrusters, and, possibly, nickel-hydrogen batteries, starting with flight 5.

Many of these "first" applications are applicable not only to Intelsat space segment but also to commercial communication satellites in general. Therefore, Intelsat V satellites will mark a real advance in the space communications era.

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