Electric Propulsion for Commercial Applications: In-Flight Experience and Perspective at Eutelsat

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Abstract: **Eutelsat launched its first satellite in 1983 and, with a fleet of 32 geostationary satellites, Eutelsat is today Europe's most long-standing satellite operator and one of the world's leading satellite operators. The procurement of telecom platforms using Electric Propulsion dates back to mid 90s with SESAT-1 (EUTELSAT 16C) that was launched in 2000. Then, a second platform, KA-SAT (EUTELSAT KA-SAT 9A), was launched in 2010. The paper presents the design description and the results of the in-flight experience of these two platforms. Besides, an overview of the EP long flight heritage is provided to show the level of maturity and reliability reached by this propulsion technology for commercial applications. Finally, some considerations from the operator point of view are also discussed regarding the design of future EP telecom platforms.**

Nomenclature

BOL = Begin Of Life
CPS = Chemical Propulsion System
EP = Electric Propulsion
E/W = East West
GEO = Geostationary Orbit
GTO = Geostationary Transfer Orbit
HET = Hall Effect Thruster
ISK = Inclination Station Keeping
MMH = MonoMethylHydrazine
NTO = Nitrogen TetraOxide
N/S = North South
PEWM = Pulsed East West Manoeuvres
PPOL = Pulsed Pitch Off Loading
PPS = Plasma Propulsion System
SPT = Stationary Plasma Thruster
TOM = Thruster Orientation Mechanism
TMA = Thruster Module Assembly
XFC = Xenon Flow Control
XRFS = Xenon Regulator & Feed System

I. Introduction

CREATED as an international organisation in 1977, Eutelsat launched its first satellite in 1983 and became a private company in 2001. Eutelsat's long and rich track record makes it one of the most experienced

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commercial satellite operators in the world. With a fleet of 32 geostationary satellites, Eutelsat is Europe's most long-standing satellite operator and one of the world's leading satellite operators. Eutelsat's in-orbit resources are positioned in geostationary orbit between 15° West and 172° East. From these premium orbital positions, the Eutelsat satellite fleet is able to serve two thirds of the globe, users in 150 countries in Europe, Africa, Asia and the Americas, from the East Coast of North and South America through to the Asia-Pacific coast.

Although satellites that use chemical propulsion for both GTO to GEO orbit transfer and station keeping manoeuvres still represent the majority of Eutelsat's fleet, the procurement of Eutelsat telecom platforms using Electric Propulsion (EP) dates back on mid-90s. SESAT-1 first and then KA-SAT are the two platforms in the Eutelsat fleet using Electric Propulsion. Their records of operational and flight performance data have shown satisfactory results with respect to Eutelsat requirements. Furthermore, in some cases, flight performances have been even better than the expected ones. A design description of these two spacecraft and their operations and flight performance are presented hereafter. Moreover, a Eutelsat perspective of aspects of Electric Propulsion implementation that can influence the development of future platforms using EP is also given.

II. The SESAT-1 (EUTELSAT 16C) Spacecraft

In mid-1995, Eutelsat decided to order a satellite from NPO-PM to satisfy the telecommunications needs in Central and Eastern Europe. The satellite, called SESAT-1 (Siberian-European SATellite), was designed to provide 18 Ku channels for a minimum operational lifetime of 10 years.

With a launch mass of about 2551 kg, SESAT-1 was launched from Baikonour in April 2000 and was placed directly into geostationary orbit by a Proton K-BlockDM launcher. It was first operated at 36° East and then relocated to 16° East. SESAT-1 – whose commercial name is today EUTELSAT 16C - enables the provision of a wide range of telecommunications services over a very large geographical area, from the Atlantic Ocean to Eastern Russia, including a large part of Siberia.

Adapted from GALS and EXPRESS satellites, the SESAT-1 is a MCC-727 platform designed around a pressurized container which houses most of the platform equipment. Solar arrays are designed on 2 wings mounted on a single shaft driver able to provide 5.6 kW at BOL with an area of about 61 m^2. The output power at 40 Volts was about 5 kW BOL with sunlight and down to 3.3 kW in eclipse. The spacecraft is 3-axis stabilized with momentum wheels.

Figure 1 shows SESAT-1 in the stowed configuration.

Figure 1. SESAT-1 satellite in the stowed configuration

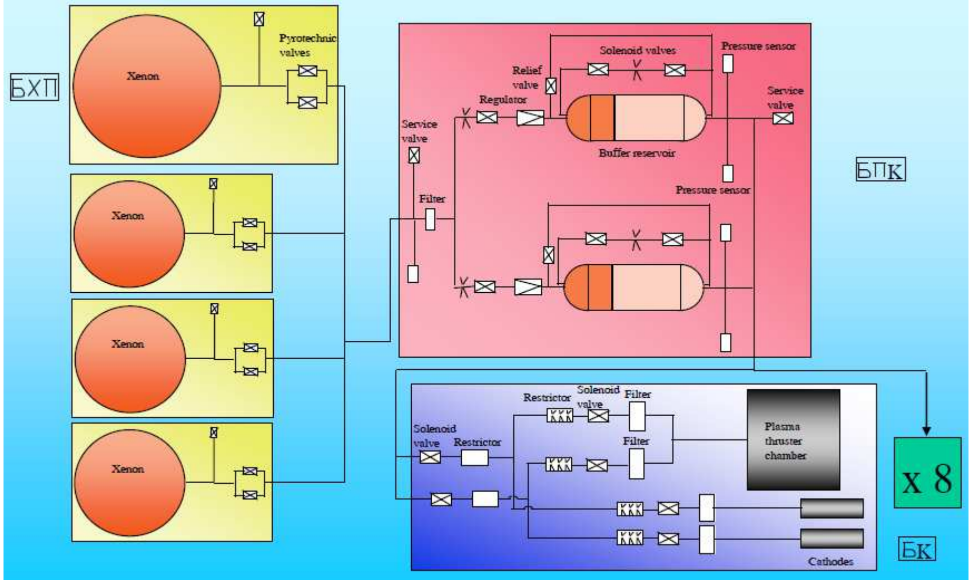

Figure 2. Schematic of the SESAT-1 Propulsion system

The propulsion subsystem is composed of a Xenon SPT Propulsion system for station keeping and orbit control and of hydrazine thrusters for attitude control. All components of the propulsion subsystem are Russian built.

In detail, the Electric Propulsion system (Figure 2) is composed of 4 tanks for Xenon storage up to 250 bar, a pressure regulation unit with 2 buffer reservoirs able to deliver the Xenon at around 2.5 bar to the thrusters and 8 SPT assemblies. A power supply provides the power to the subsystem, controlling the propellant feed lines as well as the selection of the operating thrusters. Each thruster assembly is composed of a Xenon flow control unit and a Hall effect thruster SPT 100 manufactured by Fakel. This 1.5 kW thruster is able to provide a nominal thrust of 83 mN at an Isp of 1520 s (anode voltage of 300 V) for a total impulse of 670 kNs equivalent to more than 2200 hours at nominal thrust. Each thruster is equipped with 2 redundant cathodes that are periodically cycled in accordance with the NPO-PM and Fakel recommendations.

The SESAT-1 satellite in its in-orbit configuration with solar panels and communications antennas deployed is shown in Figure 3.

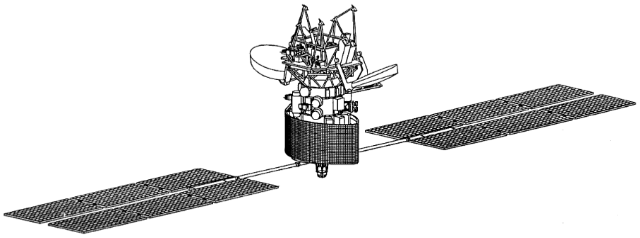

Figure 3. SESAT-1 satellite in the deployed configuration

III. The KA-SAT (EUTELSAT KA-SAT 9A) Spacecraft

KA-SAT is a high throughput telecommunications satellite able to provide broadband Internet access services across Europe and some parts of the Middle East and North Africa. KA-SAT's revolutionary concept is based on a payload with 82 Ka-band spotbeams connected to a network of ten ground stations. This configuration enables frequencies to be reused, taking total throughput to beyond 90 Gbps and making it possible to deliver Internet connectivity for more than one million homes, at speeds comparable to ADSL.

KA-SAT – whose commercial name is today EUTELSAT KA-SAT 9A - was manufactured by EADS Astrium, based on the Eurostar E3000 platform, with a total weight of about 6.1 tons. It was launched from Baikonour by Proton Breeze M in December 2010 and was positioned at 9° East for a design lifetime of 16 years. Solar arrays are composed of 2 wings of 4 panels each with an overall area of about 71 m^2 able to provide up to 16 kW at BOL with a bus voltage of 50 V. The spacecraft is 3-axis stabilized with momentum wheels. In Figure 4 the KA-SAT spacecraft in deployed configuration.

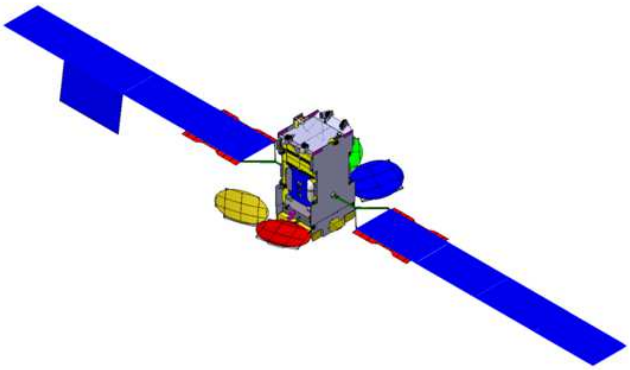

Figure 4. KA-SAT satellite in the deployed configuration

The propulsion system is composed of both Chemical Propulsion System (CPS) and Plasma Propulsion System (PPS). The CPS is used for all transfer orbit maneuvers including the final deorbiting, EW maneuvers, attitude control and wheels off-loading as necessary. The PPS is used for N/S station keeping maneuvers, orbit inclination and eccentricity control. The KA-SAT CPS is based on the generic EUROSTAR 3000 design with 4 propellant tanks (2 NTO + 2 MMH) of 590 litres with a total capacity of about 2630 kg, a Helium tank to provide pressurization, a 450 N apogee engine and fourteen 10 N reaction control thrusters. As shown in Figure 5, the PPS is mainly composed of a Xenon storage tank (XST) with 300 kg of maximum capacity, an electronic pressure regulator (XRFS), two 2-axis gimbaled thruster module assemblies (TMAs) and 2 power processing units (PPUs) along with their associated pipework and harness. Each TMA comprises 2 SPT-100s manufactured by Fakel able to provide a nominal thrust of 82 mN at a nominal Isp of 1540 s (anode voltage 300 V) for a total impulse of $2\cdot10^6$ Ns, an associated Xenon Flow Controller (XFC) a pointing mechanism (TOM) bearing and canting the SPTs with its associated thermal hardware and 2 filter units (FUs) one per thruster. The thrusters are nominally canted at approximately 45° to the spacecraft Z-axis (the axis passing through the apogee engine axis of symmetry) to ensure the thrust axes pass through the centre of mass of the spacecraft. The use of TOM can guarantee a thrust axis excursion of ±12° with respect to the nominal position. The PPU controls the selected SPT and its associated XFC

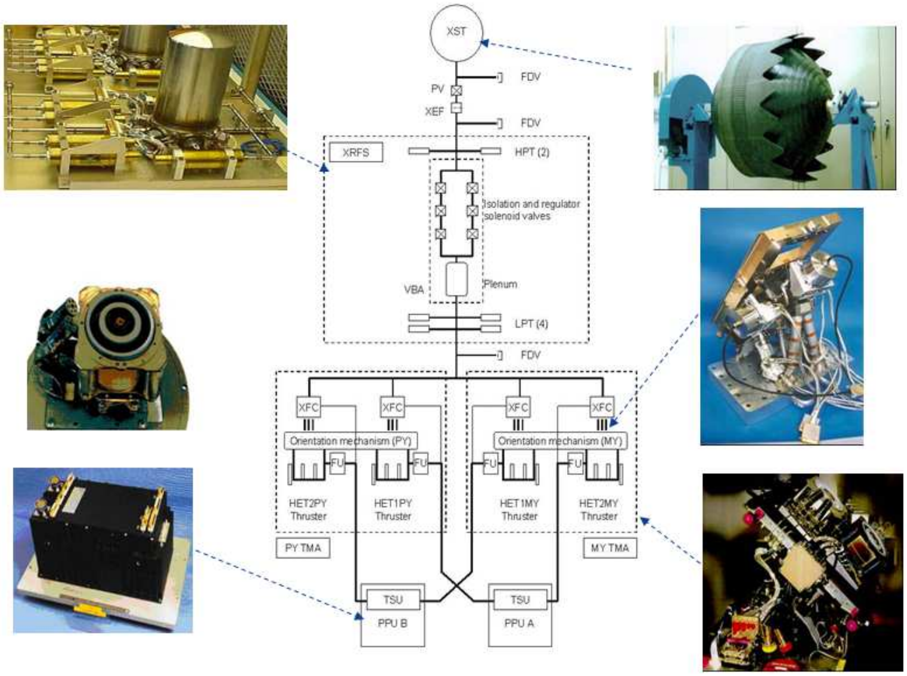

Figure 5. KA-SAT Plasma Propulsion System

on the basis of programmed procedures and commands received from the on-board computer. In terms of redundancy and reliability, the PPS architecture provides two completely independent thruster/PPU branches where each PPU is coupled to both prime and redundant system buses.

IV. SESAT-1 and KA-SAT Operations and In-Flight Experience

A. SESAT-1

As described in Section II, the SESAT-1 Plasma propulsion system has 8 thrusters SPT 100, 4 perform station keeping N/S and E/W and other 4 are mainly to perform orbit acquisition and relocation if required.

After separation from the Proton-BlockDM and direct insertion in GEO, SESAT-1 station acquisition was performed by using the 4 SPTs (2 prime + 2 redundant) mounted on the E/W faces. Regular station keeping manoeuvres to keep the satellite within its allocated orbital slot, i. e. ±0.1 degree N/S and E/W, are performed by other 4 inclined SPTs, 2 mounted on the North face and two mounted on the South face. During equinox, a combination of the inclined thrusters is used to achieve the desired control ΔV. During summer season only North face thrusters are used whereas during winter only South face thrusters are fired. Thanks to the ranging data collected every hour from 2 ground stations used alternatively, it is possible to perform an accurate estimation of the orbit data and of all acceleration components given by each thruster. By correlating orbit EP control firings with attitude control actuations done by chemical thrusters, a derivation of performance factors is possible. These performance factors are then used to optimize the station keeping strategy (e.g. in relation to the E/W station-keeping needs) and therefore to save propellant.

Although 2 SPT 100 thrusters can operate simultaneously on SESAT-1, the nominal on-station operations are performed by using 1 thruster at a time. Different operational constraints need to be respected while executing station keeping manoeuvres such as the maximum and minimum cathode/thruster on time and the minimum interval between consecutive manoeuvres. Moreover, no thruster operation during eclipse period ±1 hour for EW thrusters is possible.

As regards the station keeping profile, 1 maneuver per day is generally performed 7 days out of 7. During Equinox, 2 maneuvers per day are performed. Typically, manoeuvres near equinox are longer than the ones near solstice period.

Spacecraft attitude control is performed by using hydrazine thrusters, a pair of thrusters for each axis. However, a low level pulsing is required by these thrusters as main attitude control requirement is during initial acquisition, station keeping burns and wheels unloading.

To date, SESAT-1 has accumulated a total firing duration of almost 5500 hours, in which the most used SPT 100 thruster has been firing for about 1600 hours and the most used cathode for almost 1000 hours. SESAT-1 was designed for 10 years lifetime and after 13 years of service it is still operating properly with no critical anomaly to report.

B. KA-SAT

After separation form the launcher in GTO, KA-SAT has performed its orbit acquisition by means of 4 apogee burns using the chemical system. These LEOP manoeuvres consumed most of the chemical propellants, about 91%. The remainder is used for attitude control during operational life and re-orbiting at the end of life (some back up to the EP station-keeping and inclination manoeuvres is also available). During spacecraft operational life, N/S station keeping is performed by means of Electric Propulsion whereas E/W manoeuvers and spacecraft attitude control are performed with chemical propulsion by using the 10 N thrusters.

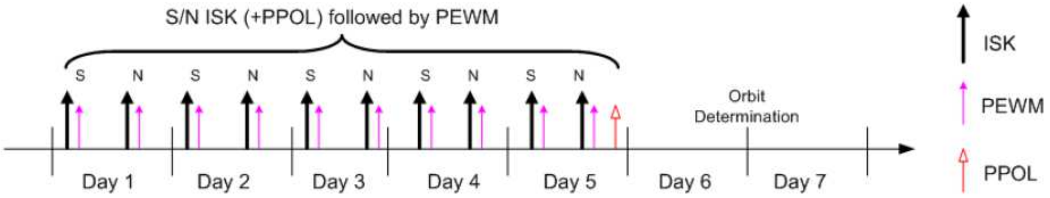

Figure 6: KA-SAT station keeping profile

A typical station keeping profile of KA-SAT for a cycle of 7 days is shown in Figure 6. For 5 days, combined inclination/eccentricity control is done with 5 pairs of N/S maneuvers by using plasmic propulsion (ISK). Another day is used for longitude drift control done with chemical pulses for E/W maneuver (PEWM) after ISK maneuvers. During this phase and after the PEWM, chemical pulses are also used to offload residual pitch angular momentum (PPOL). The sixth day of the cycle is for assessment and planning. Only two telecommands (TCs) are required to upload a maneuver (ISK, PEWM or PPOL) in the Master Schedules that offers the capacity to upload more than 2 weeks of station keeping in advance. The ISK phase duration lasts approximately 120 minutes but this duration could vary depending on the period of the year.

As for SESAT-1, different constraints need to be respected while executing the ISK and PEWM manoeuvres. After 2.5 years of service, KA-SAT has accumulated a total firing duration of more than 2200 hours. The most used SPT 100 thruster has been firing for a little bit more than 1000 hours and the most used cathode for about 575 hours. No critical anomaly to report.

C. General Considerations

Apart from SESAT-1 and KA-SAT, the remaining Eutelsat fleet is at present composed of satellites using only chemical propulsion for all their functions, from the orbit transfers to the station keeping.

Nevertheless, independently from the type of platform considered, both Electric and Chemical platforms in Eutelsat fleet have proved to be very reliable during their operational lives. In fact, flight performances across the fleet have generally confirmed the analyses and predictions presented by the manufacturers during the procurement phase.

However, comparing Electric and Chemical platforms, some considerations can be done from operations side. There are, in fact, significant differences in the way these two types of platforms are operated but no particular difficulties or critical constraints are added in the case of Electric platforms.

Concerning the station keeping strategy, a typical station keeping profile for platforms using chemical propulsion envisages 1 N/S and E/W manoeuvre every 15 days in which the selected thrusters generally operate in the range of few minutes in a pulsed mode. On the other hand, for Electric Propulsion platforms, station keeping maneouvres are implemented more frequently. As previously described, generally they are done 5 or 7 days out 7, with a couple of manoeuvres per day that last of the order of two hours each. However, as for chemical propulsion, operations for Electric platforms are not done manually and all TCs are planned in advance and sent autonomously by on-ground satellite control centers. Therefore, the higher frequency of the manoeuvres for EP platforms does not imply more complexity for controllers’ work, but just a different planning. Nevertheless, if the station keeping profile for EP platforms does not impact on the on-ground control complexity, a higher level of autonomy is required on the spacecraft able to elaborate the TCs received, implement them and control in real time the spacecraft parameters for all duration of the manoeuvre.

A second consideration is related to sudden manoeuvres. As three orders of magnitude separate the thrust level of chemical thrusters from the low thrust of plasma thrusters, a longer burn is needed for EP to obtain the same ΔV. Therefore, EP does not allow the spacecraft to react swiftly to sudden disturbances. However, most of the manoeuvres requiring a fast reaction of the spacecraft are mainly in the LEOP, relocation and deorbiting phases which are largely planned in advance and then can be also implemented with a different thrust profile by using low thrust from plasma thrusters. The additional sudden manoeuvres potentially necessary during the spacecraft lifetime could derive by hazardous objects/debris that could accidentally cross the spacecraft orbit. Nonetheless, even in that case, information to the satellite control center is provided some days in advance when the object is detectable and this time frame is sufficient to implement a low-thrust correction manoeuvre to avoid any collision. Other disturbances caused by unpredictable failures (e.g. wheel seizing) would normally be accommodated by the attitude control system.

Another consideration concerns the limitation in power deriving from the Payload need and interactions at system level. As regards Eutelsat experience, spacecraft power subsystem (e.g. solar array and battery) is always sized for telecommunication payload needs and for Plasma thrusters activation, so this has never constituted an operational constraint or problem. Besides, neither critical impingements on sensible surfaces (i.e. solar arrays), nor interference between plasma thrusters plume and transponder transmissions at Ku-band and Ka-band frequencies have never been observed during SESAT-1 and KA-SAT operational lifetime.

A final consideration to be done is on the impact of a failure on both types of platforms. Although at present the Eutelsat experience has not recorded any critical failure for both Chemical and Electric platforms during the operational lifetime, the criticality of each failure is generally more dependent on the specific platform design than on the type of propulsion used on-board. For instance, a thruster leakage can be more critical for chemical propulsion platforms where the higher mass flow of chemical thrusters could have a more important impact on the spacecraft attitude and on the loss of propellant. Therefore, a fast reaction from on-ground controllers is needed. On the other hand, the partial or complete loss of a solar array can be more critical for Electric Propulsion platforms resulting in a lack of power for nominal operations. However, for both kinds of platforms, a good design shall take into account these potential issues and mitigate the impact on the required platform performance.

V. Electric Propulsion on Future Telecom Platforms: the Operator point of view

The successful demonstration of sustained capability of EP during the in-flight experience of SESAT-1 and KA-SAT is doubtless a notable result and is for Eutelsat a valuable flight heritage concerning EP systems.

Nevertheless, at present, an extensive flight heritage of EP systems has already been demonstrated by other telecom platforms as well as scientific platforms. In addition to the fact that EP systems using Russian built using HETs have been flying since the 1970s, in the last decades many successful missions were accomplished using EP systems in which the Hall effect thrusters Fakel SPT 100[1], the Snecma PPS-1350[2] or ion engines with an input power up to 2.5 kW (NSTAR, XIPS 13 cm, T5, RIT 10 cm, ETS-8, μ10) were extensively used[3,4,5,6,7,8,9].

Further missions were successfully accomplished using EP systems with higher power levels (up to 5 kW). To date, 14 of the Boeing 702 telecom satellites with a total of 56 XIPS 25-cm thrusters (4.5 kW ion engines) have been successfully launched and are in operation[10,11]. The first one was launched in 1999 so a long flight heritage already exists and no critical anomalies were reported to the author's knowledge. After launch, these thrusters are first used for orbit raising and then provide all of the propulsion requirements for orbit control including N/S and E/W station keeping, attitude control, and momentum dumping. During orbit raising, these thrusters are used in the "high power" mode - 4.5 kW, 165 mN thrust at a specific impulse of about 3500 s – that requires nearly continuous operation by two of the thrusters for times of 500 to 1000 hours, depending on the launch vehicle and satellite weight.

Another telecom platform using a "high power" EP system is the AEHF-1 satellite manufactured by Lockheed Martin Northrop Grumman. It was launched in 2010 with both Chemical and Electric Propulsion systems on-board. The Electric thrusters mounted on-board are the 4.5 kW BPT-4000 (290 mN at a specific impulse of 1800 s) manufactured by Aerojet. After launch, due to a critical failure of the apogee engine, the EP system was ignited to allow the spacecraft to perform the orbit raising and reach the final orbit. The spacecraft took longer than originally planned to perform the orbit transfer, but in the end the mission was successfully recovered.

All the successful results here above discussed confirm the high level of maturity reached by Electric Propulsion also for commercial applications. As a result, today spacecraft manufacturers can rely on a certain number of flight proven and reliable EP technologies and packages to support proposals for different platforms in the coming years.

Concerning future telecom platforms in which EP will play a fundamental role as primary propulsion system, Eutelsat is of course watching with interest any design evolution proposed by manufacturers without being in principle adverse to the introduction of new or different technology.

However, it seems quite evident today that a winning design solution covering the needs of all missions does not exist. Each mission can have very different requirements and aims for different markets. Consequently, for any particular case, there can be many considerations and these may have to be weighed in detail to arrive at the best solution (which is typically driven by the specific economics). From an operator perspective, a proposed design may be evaluated on criteria such as timeliness of placing a service in orbit, maintaining a competitive edge, reduction of cost per transponder or other service aspects. The following paragraphs give a Eutelsat perspective of aspects of EP implementation that can influence the market development:

- *Launch strategies and market of new launchers:* The use of EP systems can influence the platform design in one of the two senses. It can allow a reduction of the spacecraft launch mass in case of fixed payload mass or alternatively it can increase the payload mass for a fixed launch mass. Therefore, two limiting design options – both economically attractive - could be achieved. The first option could move towards smaller platforms that can be delivered in GTO from a cheaper launcher already available on the market. A longer time to reach the final orbit due to a low-thrust orbit raising would be justified by a significant reduction of launch costs. The second option could move towards heavy platforms that could be delivered directly in GEO and that will almost double the payload mass with respect to state-of-the-art telecom platforms design. However, this second option represents a longer term alternative as it relies on the development of a more powerful launcher not yet available on the market. Between these two limiting cases, there could be a certain number of intermediate solutions in which state-of-the-art platforms with dedicated EP systems can perform the orbit transfer from the release orbit. In spite of a longer transfer time, the propellant mass saved with respect to chemical propulsion would turn into an increase of the payload mass.

  Indeed, the development of more powerful launchers and then a change in the launchers' market will play a key role for the design trade-offs of future telecom platforms. The possibility to deliver heavier masses in GTO or directly in GEO will create, yet again, new and different design options.

  Another point to be considered in this analysis is the compatibility of new platforms with respect to a wide range of launch vehicles. A new design that fits just for one launch vehicle is not desirable from the Operator point of view as it will limit the possibility to obtain competitive prices from different launch services and introduces exposure in the case of a launch failure, or hiatus.
- *Time to Orbit:* With current designs, the use of EP for orbit transfer from the release orbit to the final orbit takes longer than current LEOP phase (about 10 days). Three/four months have been generally identified as a maximum acceptable time for orbit raising, however, to the author's knowledge, these durations are, at present, not justified by any detailed economic analysis. More generally, even longer transfer times could be acceptable providing that the manufacturers will be able to limit the additional LEOP costs (e.g. by increasing the spacecraft level of autonomy, by reducing the number of ground stations to be used) and counterbalance them with a significant reduction of launch cost.

  This longer time to orbit will also impact on the Operator side. In these cases, the procurement time to service will now have to take into account the additional time to acquire the final orbit in GEO. This implies that a different approach to planning and allocation of in-orbit resources will be required.
- *EP costs*: To date, due to the higher developments costs and to a limited use of Electric Propulsion, generally EP systems are more expensive than the Chemical ones. A large use of EP systems on telecom platforms with a consequent constant demand of hundreds of thrusters per year can generate a scale economy effect resulting in a reduction of EP systems cost.
- *Compatibility with upcoming debris policy*: future platforms shall withstand the upcoming requirements from the debris policy. The proposed designs shall consider at least the possibility to vent the pressurized vessels at the end of life after de-orbiting and ensure that the final "graveyard" orbit can be reached.
- *Reliability and Risk Mitigation*: Last but not least, whatever will be the propulsion technology selected by manufacturers, no technical risks are acceptable from an operator, including outages from de-pointing and loss of transmission. Reliability of proposed EP platforms shall ensure equal or better performance than current designs and these will include robustness to ensure operations can be maintained in case of failure. Therefore, apart from relying on a successful flight heritage of the selected EP technology, a good design shall be aimed at reducing single point failures and improving the level of redundancy and robustness of the propulsion system.

VI. Conclusion

Eutelsat in-flight experience with telecom platforms using Electric Propulsion started in 2000 with the Russian built SESAT-1 spacecraft manufactured by NPO-PM. Then, a second platform, KA-SAT, manufactured by EADS Astrium with Russian built plasma thrusters on-board was launched in 2010. A design description of these two spacecraft and of their operations and in-flight experience has been presented. In both cases, in-flight data have shown to be in line with Eutelsat requirements and in some cases, they have resulted in performances beyond expectations.

Today, the successful demonstration of sustained capability of EP during the in-flight experiences of Eutelsat platforms SESAT-1(EUTELSAT 16C) and KA-SAT (EUTELSAT KA-SAT 9A), in addition to a significant number of other successful missions using Electric propulsion for both orbit transfers and station keeping manoeuvres, constitute a solid background for EP to claim a high level of maturity for commercial applications. Eutelsat is watching with great interest the development of new platforms using EP systems and - given the proper system reliability and risk mitigation as well as the economic viability of new proposed design solutions - Eutelsat is in principle not adverse to an increase in the number of platforms in her fleet using Electric Propulsion.

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