Design and Development of an Electric Propulsion Deployable Arm for Airbus Eurostar E3000 ComSat Platform

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Abstract: The new Deployable Thruster Module Assembly (DTMA) is one of the main enablers for an intensive use of electric propulsion on-board telecommunication satellites, and in particular for Electric Orbit Raising (EOR). Airbus has completed the design of this robotic arm, allowing positioning and orienting Hall-Effect thrusters in the most efficient way during all phases of a mission. This paper describes the architecture, industrial organization and qualification of this product, developed in a short time-scale in order to be flown on Eurostar E3000 satellites as soon as possible. With the launch of Eutelsat 172B in June 2017, the objective has been reached.

I. Background

AIRBUS has been flying electric propulsion on its telecommunication satellites for more than one decade [1], and has accumulated more than 30.000 hours of in-orbit operations for station keeping on its Eurostar E3000 flagship platform. Electric propulsion has recently taken a dramatic boost thanks to the maturity of this technology – now well-demonstrated in orbit – and to new launching opportunities such as SpaceX's Falcon 9, evolution of Ariane 5 (lower position, new fairing), or Soyuz in Kourou. In consequence, many Airbus' customers among ComSat operators are now keen to trade delaying the entry into operational service of their satellite by a few months in favor of a much reduced transponder cost, which is the main promise of electric propulsion: the initial phase of nearly-continuous electric thrust allows the satellite to reach the GEO arc from the launcher injection orbit in few months, while saving hundreds of kilograms of propellant. This phase is called Electric Orbit Raising (EOR).

Thanks to its exceptional in-flight experience in operating Hall-Effect Thrusters (HET), Airbus was able to offer as soon as 2013 mature solutions for implementing this game-changing EOR on its well proven Eurostar E3000 satellite platform, even before starting its new-generation platform development in the frame of the NEOSAT program.

One of the key enablers of the EOR version of E3000 (E3000e) is the Deployable Thruster Module Assembly (DTMA), which includes a versatile system that deploys and points Hall-Effect Thrusters (HET) in the optimal direction during each phase of the mission: the EOR (or transfer) phase, lasting any time between a few weeks up to maximum of 6 months; the operational mission of 15+ years, where electric propulsion is dedicated to station-keeping maneuvers and momentum control; the satellite repositioning, if needed; and the transfer to graveyard orbit at end of life.

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The quick development of the DTMA was only made possible by the experience gained by Airbus on similar assemblies, and in particular with the development of the Advanced Thruster Module Assembly (ATMA) [2]. The ATMA is a 2-axes pointing mechanism equipped with 2 Hall-Effect Thrusters. It is qualified and is the current reference product for use of electric propulsion for classical North-South Station Keeping maneuvers in the E3000 series: recent examples of satellites using the ATMA are Sky Brasil-1 and SES-10 satellites.

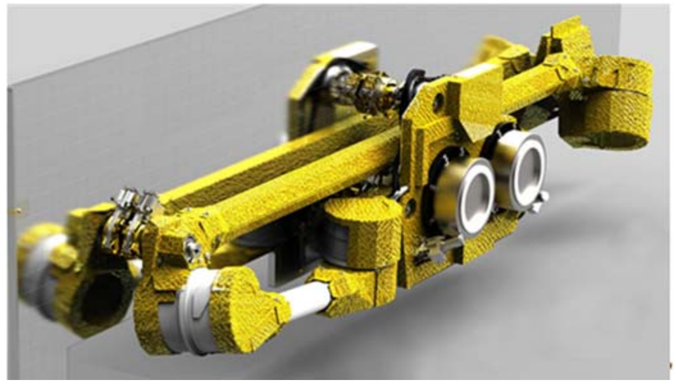

Figure 1. General view of the DTMA.

II. Objectives of the development

The DTMA development was initiated in 2011. Its technical objectives were three-fold and were embedded in the DTMA specification since day-1:

- First, to optimize the thrust geometrical efficiency of station-keeping maneuvers by approaching the thrust direction to the North-South direction (Y axis of the satellite frame), the direction of the dominant luni-solar perturbation.
- Second, to enable performing the EOR phase with the maximum thrust given the available power to minimize the duration of EOR. For that objective, the selected solution consisted in pointing the North and South deployable arms so that all electric thrusters (the same ones used for station keeping maneuvers) point toward the same direction, chosen as the longitudinal direction of the satellite (Z-axis of the satellite frame).
- Third, to base the design, manufacturing and qualification on standard building blocks, easily re-usable on future platforms.

Having in mind these three objectives, the main development constraint was to have the shortest possible time to market, while guaranteeing Airbus reputation for high-quality standards. This was possible by designing the system around reliable off-the-shelf components, already flight-proven on Airbus telecommunication platforms, so as to avoid any long learning process in accommodating and using them.

Also, the DTMA was designed to be compatible or easily updatable with different Electric Propulsion (EP) technologies, as these technologies experience rapid evolution nowadays. Here again, the motivation was time to market, allowing Airbus to offer EOR as soon as early 2013 to its customers, while minimizing the upgrade when more effective technologies are qualified. The compatibility was limited to the HET technology, which currently provides the best compromise for ComSats between mass efficiency (characterized by the Specific Impulse), time efficiency (thrust-to-power ratio) and heritage. Moreover, several thruster suppliers develop equivalent competitive products over the world, including in Europe, which strengthens Airbus supply chain.

Other significant side objectives were then added to further boost the value-for-money of this development: in particular, the ability to re-use the developed technology for deployment of antenna reflectors, and also improve the DTMA so that it allowed implementing full-electric missions (3-axes system was preferred to a 2-axes system). Finally, minimal stowed volume and mechanical interfaces compatible with the E3000 platform without modifications were also required to this equipment.

III. Architecture

The DTMA is divided in two components:

- The Deployment and Pointing System (DPS): this is the robotic arm that unclamps after launch and provides the motorization to achieve the required kinematics.
- The Plasma Thruster Module (PTM): this is the deployed system, composed of a structural plate where the thrusters and mass flow rate controllers are installed. This plate also provides thermal control for the thrusters and flow controllers, in particular insulating the thrusters from the DPS.

This split is the best answer to the versatility requirement:

- The DPS is in charge of all the motions and includes all mechanisms; it provides positioning and orientation, and it is controlled by the Attitude and Orbit Control Systems (AOCS) during flight. It is as independent as possible from the Plasma Propulsion Subsystem (PPS): its only link is that power and Xenon transit through it to reach the thrusters, which defines some minimal requirements in relation with the PPS. Hence, the DPS is independent from the type of thrusters and is qualified for once, the only modification being the detailed definition of the harness going through the DPS towards the thrusters.

- In contrast, the PTM is specific to each thruster. Airbus first designed a PTM around the SPT-100 thruster supplied by Fakel. The second version, compatible with SPT-140D, also supplied by Fakel, has been designed and qualified and is the current reference PTM. The third version is compatible with the PPS-5000 thruster supplied by Snecma.

IV. Industrial organisation

The DTMA development has been led by a dedicated system team within the telecom directorate of Airbus. This team is nested in the system team developing the other aspects of the EOR (system, PPS, AOCS, operations, platform adaptations, etc.) within Airbus. The DTMA team is in charge of the technical specification of the two main components, as well as of the interface definition; it coordinates with all disciplines and establishes the DTMA performances. It also defines the industrial organization of the DTMA, leads the main Request for Proposals (RfP) for selection of key suppliers, and follows the development of each component and the production of the first flight models. It also interfaces with Airbus satellite customers to guarantee that the DTMA answers both their needs and quality standards.

The DPS design, qualification & manufacturing was allocated after a competitive selection to a team composed of Airbus MDO (Mechanical Design Office) and its Belgium partner, EHP (Euro Heat Pipes). This activity was supported by the European Space Agency (ESA), through the ARTES program, allowing Airbus to benefit from the follow-up of the development by ESA experts. The design phase was completed in 2014, the qualification phase ended early 2016, and the first two flight models were delivered in May 2016 and integrated on Eutelsat 172B, the first E3000e satellite, which was launched on June 1st 2017.

The industrial organization of the PTM is adapted to the type of thruster that it embarks and necessarily involves the thruster supplier. After a one-year concurrent engineering phase between Airbus and Fakel, an efficient industrial organization was agreed and set for the reference PTM built around the SPT-140D thruster. On one side, the structural plate design, production and assembly including all thermal hardware is under responsibility of Airbus. On the other side, Fakel is in charge of supplying a propulsion assembly composed of 2 SPT-140D thrusters including 2 flow controllers and all the necessary pipework connecting these controllers to the thrusters. Finally, Airbus only needs to transfer the propulsion assembly from the delivery jig to the structural plate.

V. Design

On each E3000e satellite two DTMAs are installed, one on the Plus Y wall (PY) of the Service Module (SM), and another one on the minus Y wall (MY) of the SM. Both DTMAs, each one made of a 3-hinge DPS and a PTM, are strictly identical.

A. Geometry

The geometry is determined as an optimum for on-station North-South efficiency while respecting all accommodation constraints – such as the avoidance of penetration in satellite parts and in CPS thruster plumes; the driving constraint is the plume-induced erosion on solar cell interconnectors. Using plume models and erosion simulation tools [3] correlated by Airbus over the years with in-flight and on-ground data, a thruster no-go area (erosion curve) was established during the preliminary design phase of the DTMA: this no-go area defines the space, in terms of position and angle, from which HET induce more-than-acceptable erosion on solar arrays.

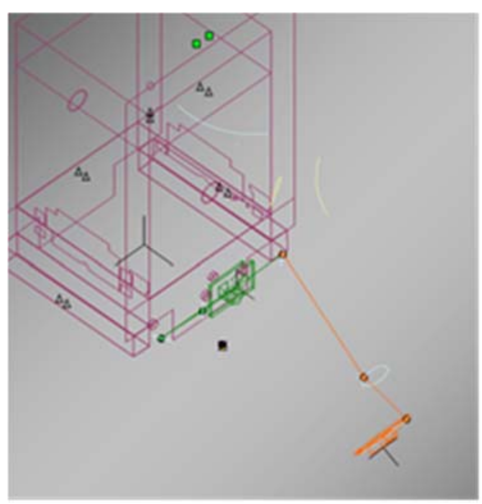

Figure 2. Visualization of the arm geometry optimization tool 'Pilot'.

For the generation of the optimal DTMA geometry, in-house optimization software – called "pilot" – has been specifically developed, derived from reflector deployment optimization tools. The positions of the hinges are mainly defined by the stowed constraints – structural hard points and authorized stowed volume – while the orientation of the hinges can be optimized. With the Degrees of Freedom available in the system for optimization, it is possible not only to fulfil the erosion curve and choose solutions that offer good clearance at deployment, but also to offer an excellent controllability in the deployed on-station configuration. The controllability is defined as the number of actuations necessary to perform a given torque for AOCS in all the controllable directions. It is important to minimize this number of steps, first in order to authorize a fast response time to perturbations for the AOCS (in particular in the minutes after thruster ignition), and second to remain within the qualification limits of the actuator. With the proposed design, and accounting for AOCS scenarios provided through dedicated simulations, it is estimated that the operation of the robotic arm will require a maximum of 14 million elementary actuations over its entire lifetime with 205,000 inversions for the worst-case hinge. This is well within the qualification limits of the selected actuator, even when accounting for demanding ECSS margins.

B. DPS design

The DPS can be decomposed into several elementary building blocks, mainly three hinges and two booms. The booms are CFRP tubes, identical in diameter and thickness, and only differ by their length: all harness and pipework are nested inside the boom. The hinges are nearly identical, allowing being qualified as a single building block. Their key asset is to minimize the intrinsic resistive torques in the DPS – despite the amount of cables and pipe necessary for the operation of the electric thrusters – in order to be compatible with a Moog type-3 off-the-shelf actuator. With the proposed arrangement, this actuator was confirmed as adequate in terms of angular step and as a good compromise between mass and actuation capacity. Moreover, it offers an impressive heritage in orbit, which is the most critical criterion for the overall reliability of this robotic arm, specified to be operated every day over more than 15 years of mission. The design of the hinge authorizes the implementation of alternative actuators, provided that they do not differ too much in terms of interface, actuation capacity and step size. Such developments are on-going in Europe and may offer more competitive European technologies to the future upgrades of the DTMA. Within the hinges, harness and cables are protected under metallic covers.

Finally, the basic building blocks are linked by bespoke fitting elements, metallic interfaces and hexapods allowing fitting the building blocks to the desired geometry. One of the key assets of the design is that all pipes and harness going from the satellite to the thrusters are almost entirely rooted inside covers or tubes, which offers a good protection against space environment, namely thermal cycling, radiations, UV and micrometeoroids.

C. PTM design

The PTM is a machined stiffened plate supporting thrusters, flow controllers and the pipework connecting them together with all associated electric harness. The plate is optimized from a thermal and mechanical point of view. The design answers some challenges, including the high temperatures reached by 5-kW class HET during long-firing combined with the fact that during EOR, the PTM could experience any Sun orientation. Besides, the flow controllers need to work in a more stringent temperature range. From a mechanical point of view, the PTM has to support the launch loads and guarantee that the thrusters are not damaged. All this leads to a challenging multi-disciplinary optimization exercise.

Each DTMA is clamped to the satellite during launch through four Hold-down and Release Mechanisms (HRM). The selected HRM are based on the Low-Shock Release Unit (LSRU), a very low-shock device developed in Europe as HRM for solar arrays and that was successfully flight-qualified during the Alphasat mission. On Alphasat, 20 of them successfully released the SA in space. The HRMs of the DTMA are accommodated on the strong points of the E3000 mechanical platform, defining in a large part the DTMA geometry, as explained below. The DPS is attached by its root hinge (screwed on the structure on the Y wall close to the X-wall position), and by one HRM at the elbow hinge (attached on the Y wall close to the other X-wall). The PTM is attached by three HRMs, also located at structural strong points (close to the shear wall and closure panels).

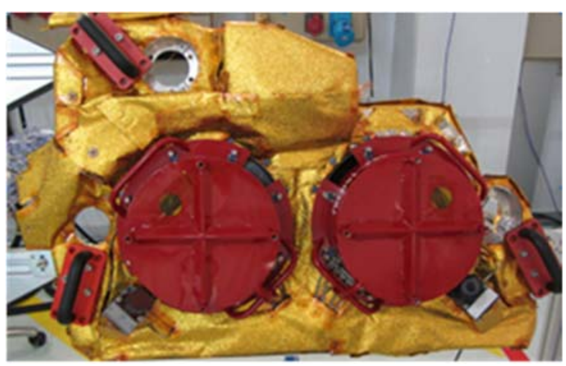

Figure 3. Front view of the PTM with two SPT-140D thrusters.

VI. Development

After some early activities, the development of the DTMA started in 2011 through the beginning of the ARTES 5.2 study with ESA. Then, the industrial phase of development was launched in the last quarter of 2012, after a competitive Request for Proposal (RfP) organized over the summer 2012 on the DPS. From that point on, the development of the DPS and of the PTM were split, with the DTMA team in charge of maintaining the coherence of the whole design, as well as the compatibility with the platform and with the EOR project objectives.

The design and qualification phase was successfully completed; the first flight set was integrated on Eutelsat 172B which was launched in June 2017.

A. DPS development

The DPS development benefits from its elegant design, using already qualified critical items. The qualification focused on the few parts not already flight proven and on verifying that the overall design fulfils all the requirements of the DPS specification.

In parallel to the preliminary and detailed design, a few breadboards and Engineering Models (EMs) were developed. Each one had a precise technical objective, mitigating the main technical risks by order of priorities:

1. The CRAS (Conduit Rotary Articulation System) breadboard: resistive torques and lifetests

This breadboard aimed at tackling two risks with direct impact on concept feasibility: first, the risk of having hinge resistive torques above the capacity of the actuator; and second, the risk of ageing of the piping and harness due to the motion.

For the first risk, the arrangement of harness and piping in the hinge was anticipated as low-torques through initial estimates. But it was necessary to verify this statement as soon as possible to demonstrate that the Moog type-3 was adequate for the hinge. Measurements were performed at various operating temperatures to verify the standard 3:1 ratio in motorization margin in all conditions.

For the second risk, leak test on the pipe and standard electrical functional tests on the harness (isolation / conductivity) were repeated over a sequence of mechanical stress tests, starting with vibration tests, shock, and then actuation life test. The CRAS breadboard campaign was successfully completed before the Preliminary Design Review (PDR) during the first quarter of 2013.

2. The Manufacturing, Assembly, Integration and Test (MAIT) breadboard: integrability

This breadboard aimed at demonstrating the feasibility of integration of the DPS. As emphasized earlier, one of the main advantages of the concept is to root all harness and piping inside booms and hinges. The MAIT breadboard proved that this advantage does not jeopardize the ability to efficiently assemble the DPS. Built out of plastic pieces at full scale and 3D printed parts, the tests were completed in time for the Critical Design Review (CDR), at the end of 2013.

Figure 4. MAIT breadboard.

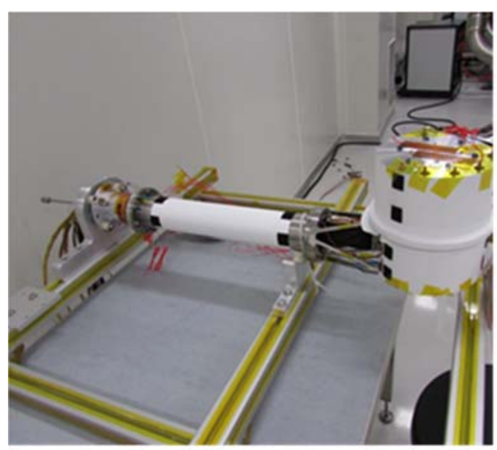

Figure 5. Engineering Model 1.

3. The Engineering Model 1 (EM1): thermal design validation

This single axis model was mainly focused on the thermal performances of the DPS. Because this robotic arm transfers up to 5 kW of power towards the electric thrusters on its extremity, it is important to demonstrate that the thermal concept is able to evacuate the heat dissipated to harness during thruster operation, while limiting the necessary thermal power in the cold cases, when the thrusters are not being fired. It was also important to show that the DPS temperature remains in the limits authorised for the Xenon feed lines, as well as qualification limits of the various parts, the actuator in particular. The EM1 was developed, assembled and tested between PDR and CDR. The campaign was completed by the end of 2013, and allowed to fully correlate the thermal model of a hinge.

4. The Engineering Model 2 (EM2): full rehearsal

This full scale 3 axes model aimed at defining the detailed integration sequence and all Assembly, Integration and Test (AIT) procedures of the DPS, testing the jigs and Ground Segment Equipment (GSE) necessary for the production phase. The EM2 was therefore started after the end of the design phase. It mitigated the risk of damaging flight hardware, by offering a rehearsal of all sequences ahead of the actual first flight set. One of the particular interests of this model concerns the deployment test, which have been performed for the first time on-ground with this model, using specific zero-g jigs, whose development and operation are considered as challenging. Deployment at supplier level were tested early 2015, and a rehearsal of deployment on a satellite dummy wall was performed in early 2016.

Also, thermal balance tests were conducted with this model to finalize correlations on the entire DPS. Finally, this model was also used to rehears the vibration campaign and qualify the vibration jigs.

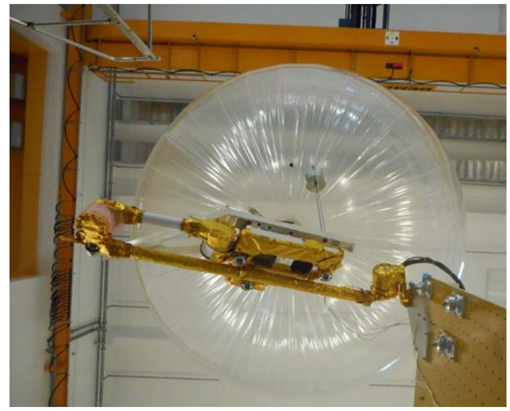

Figure 6. Engineering Model 2 during deployment rehearsal.

5. The path to full qualification

After the CDR, completed by early 2014, the qualification phase moved forward. This included intensive testing of several models: each building block was qualified independently.

a. The CFRP booms were qualified in anticipation during the year 2013. The qualification was completed by the CDR.

b. The hinge Qualification Model (QM) is designed to experience a full sequence of tests: mechanical tests, including sine vibration, random, and shock, thermal cycling, and finally actuation life-tests were performed. The QM successfully completed its test campaign during summer 2015.

c. Finally, the overall qualification of the DPS was completed by the test sequence performed on the Proto-Flight Model (PFM). This model experienced intense testing, in particular mechanical vibrations (sine and random), thermal vacuum, and deployment. The PFM was manufactured in 2015 together with the second Flight Model (FM); they both constitute the first flight set. It was delivered to spacecraft integration in Spring 2016.

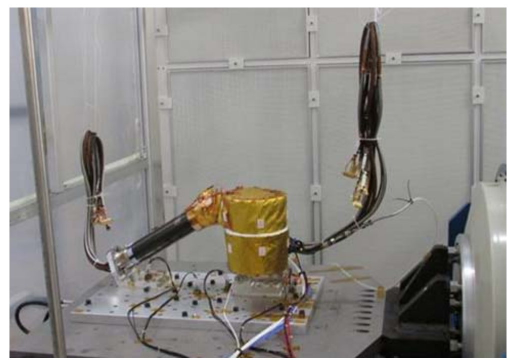

Figure 7. Qualification Model during vibration tests.

B. PTM development

Also for the PTM, a similar building block approach was followed. On one side, the selected thruster followed its own independent qualification. On the other side, the structural plate is specific to one specific thruster and one specific platform, being the interface between both. So, implementing the qualified thruster on a new platform or even changing the thruster on E3000e will only require adapting and requalifying the structural plate. The current reference PTM is based on the SPT-140D thruster, whose qualification is the key step and critical path of this development, but it is out of the scope of this paper.

The detailed design of the PTM was completed in the second quarter of 2015, with the PTM CDR.

The structural plate being an object sufficiently simple, the design validation focused on correlating its thermal interface with the SPT-140D thrusters. Thus, a PTM Validation Model using flight representative thrusters and structural plate was manufactured and assembled, also allowing validating all integration procedures. This Validation Model was used in autumn 2015 to perform a thermal coupling test between the thrusters and the structural plate: the thrusters were fired under different hot and cold thermal environments so that the complete thermal model could be correlated.

The first flight set of two PTMs was assembled and delivered in July 2016.

C. First DTMA flight models assembly and early flight experience

The DPS and PTM first flight sets were assembled in July 2016 to form the first DTMA flight set and be integrated on Eutelsat 172B, the first E3000e satellite. E172B was launched on June 1st 2017 with its two DTMAs. After separation, both DTMAs were successfully deployed and reached their transfer position. The electric thrusters were ignited and transfer towards final orbit slot was initiated. In September 2017, when this paper was written, the transfer phase was close to be finished and both DTMA had answered all AOCS solicitations nominally and without any anomaly.

VII. Conclusion

The DTMA is a very promising and innovative product, and literally gives "wings" to the Eurostar E3000e product line. The development of this product has represented an intense phase, because of all the challenges it gathers: technical excellence, quality and reliability, and finally short duration of the development, in order to propose a reliable EOR solution in the shortest timescale to Airbus' customers. Tackling such challenges successfully was only made possible by a smart design, assembling already-qualified key elements. With the successful qualification of this equipment in 2016, Airbus completed a major milestone of the E3000e development, before the launch of Eutelsat 172B in June 2017.

The next step, once Eutelsat 172B reaches its orbit slot, is moving the DTMAs into their station-keeping position and using them for all station-keeping maneuvers. The second and third flight sets have been integrated on SES-12 and SES-14. Three other flight sets are being produced.

In parallel, Airbus is already working on an improved DTMA, adapted to its new generation Eurostar Neo platform, developed in the frame of NEOSAT. Thanks to the experience gathered during the development of the first generation DTMA, the new generation DTMA will be optimized and its development will be even faster.

Acknowledgments

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