Development of the Integrated Thruster Unit ITU100 and ITU140

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Abstract: In the aerospace industry there is a great interest in the use of thrust vector control mechanisms. So, on commercial spacecraft (S/C) thruster orientation mechanisms (TOM) are used, which allow to optimize the number of EP thrusters in the spacecraft and provide the thruster rotation to perform both the main tasks of maneuvering and compensation for the deviation of the thrust vector from center of mass of S/C.

One of the problems of using the TOM with EP thrusters is that the installation on the spacecraft EP thrusters and TOM from different suppliers requires development of complex non-unified integration procedures. Therefore, this solution for integration of EP thrusters with TOM is not optimized in terms of their further joint operation on board a spacecraft.

For the purpose to solve this problem and create competitive thruster units with a controlled thrust vector, the Integrated Thruster Unit ITU was designed in the frame of cooperation between EDB Fakel and RUAG Space, combining ready-made solutions of EDB Fakel in terms of EP thrusters and RUAG Space in terms of TOM.

The Integrated Thruster Unit ITU is unified for the integration of the SPT-100 and SPT-140D-based propulsion systems with the TOM basic structure that provides a thrust vector control with rotation in two degrees of freedom in a wide angular range, mechanical loads damping system and a thermal control system of the propulsion systems components.

Currently two TOM-based thruster unit configurations are developed. ITU100 includes two thruster systems with SPT-100 thrusters. ITU140 includes one thruster system with an SPT-140D thruster.

TOM has successfully passed both stand-alone qualification test with an integrated SPT-100 and SPT-140D mock-ups at RUAG Space and qualification test as part of the thruster units ITU100 and ITU140 at EDB Fakel.

In this paper the design overview of the integrated thruster units ITU100 and ITU140 and a brief description of their qualification results will be presented.

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I. Introduction

One of the problems with the use of electric propulsion (EP) for satellites is that the satellite manufacturer has to integrate the EP Propulsion system and the Pointing Mechanism from different suppliers so the resulting thruster unit is not optimized for performance. RUAG Space has recognized this situation and has been working with EDB Fakel, one of the leading suppliers of electric propulsion systems, to develop an Integrated Thruster Unit (ITU) that can utilise a range of EP Thruster combinations using a basic structure that provides the thrust vector pointing, shock isolation and the thermal control of the EP subassembly on one integrated unit which can be easily built into a satellite.

RUAG Space has developed the Thruster Orientation Mechanism (TOM) that can currently support one SPT140 thruster or two SPT100 thrusters. The TOM is based on a common lower structure with a tailored upper thruster support structure.

The two TOM QM models were based on a common lower structure, but differed at the level of the thruster mounting, and with the support of the EP subsystem (EPS). To achieve this, it was necessary to make compromises during the design process, which also had a significant impact on the final design of both mechanisms.

The TOM QM models have both been subjected to a classical qualification campaign, which will include a life test on the complete system.¹

This paper will describe the ITU configuration with both thruster application and the ITU qualification campaign results at the EDB Fakel that aims to confirm SPT operation simultaneously with TOM rotating.

Finally, it will be shown applicability for satellites and potential application the new SPT generation for ITU configuration.

II. Design overview of the ITU100 and ITU140 and their characteristics

A. ITU baseline design

Integrated Thruster Unit (ITU) is developed as result of a joint work between EDB Fakel and RUAG (Switzerland) and is an optimized off-the-shelf integration solution of EP and Pointing Mechanism for customers. ITU consists of an SPT-based thruster system and a two-axis precision pointing mechanism TOM, which was derived from EPMEC pointing mechanism, utilized in SMART-1 spacecraft.

Two thruster system configurations are developed for ITU. ITU140 includes one thruster system EPS-140 based on SPT-140D thruster. ITU100 includes two thruster systems EPS-100 based on SPT-100B thrusters.

The ITU features design flexibility in respect of interchangeability between two thruster system configurations (see on the Fig. 1). EPS-100 and EPS-140 thruster systems have similar interfaces except for the thrusters and therefore TOM can be used as a common-type integration platform taking into account differences between designs of thruster plates and radiators of two thruster system configurations.

ITU is protected from extreme space conditions by shock damping system and thermal control system. The shock damping system provides damping of the vibration and shock loads transmitted from the spacecraft to the thruster and XFC modules during launch vehicle flight.

The thermal control system (TCS), which consists of MLI (Multilayer Insulation) and radiator, is necessary to decrease a heat flow descending from the thruster to the low temperature elements. TCS also includes heaters, which maintain the minimum required EPS temperatures at extreme low temperature conditions.

All electrical circuits of ITU sub-assemblies are routed to electrical connectors located on a single bracket.

Redundancy of the electrical components of the ITU is created on the principle of separate rolling redundancy, in which the functions of the main component are transferred to the backup only when it fails.

ITU can be provided with a separate Electronic Control Unit (ECU), which can control up to 4 separate ITU units on a spacecraft using an on-board computer.

ECU controls the TOM based on the telemetry information, interpreted by ECU and generated by the TOM sensors, and ensures that the TOM receives power.

Figure 1. ITU interchangeability scheme.
B. Electrical propulsion system design and characteristics

Depending on the mission to be flown, the ITU will utilise either two SPT100 or one SPT140 thrusters.

Each thruster system consists of a thruster (or thrusters) and XFC modules, between which pneumatic connections are realized using pipelines, which consist of three parts:

- not-movable part fixed on the thruster mounting plate and the baseplate (including a connection pipe with a filter);
- flexible part consisting of two sets of three spirals each to allow the bending movement during operation in orbit;
- upper flexible part to allow the vibration of the thruster mounting plate assembly during launch.

General view of the EPS-100 and the EPS-140 configuration are shown on the Fig. 2, and 3.

Pipelines are made of stainless steel that has been successfully tested on the BB1 breadboard test – as the TOM, spring shape tubes were subjected to more than 110’000 rotating cycles including full range cycles and the rest, small angular movements of ±5° and ±1° movement cycles at different starting positions inducing high oscillating stresses in the tubing. BB1 test fixture with pipelines is shown on the Fig. 4.

BB1 test had validated the following

- stainless steel pipelines survivability during operating lifetime test;
- The ideal shape of pipelines is a spring (Experience from previous TOM developments (e.g. SMART-1));
- pipelines withstand the stresses resulting from the enforced deformations during operation and have sufficient resistive torque margins.

EPS harnesses have a not-movable (i.e. fixed) and flexible parts. The flexible parts of harnesses are routed in braids made of stainless steel named as flex cable guiding and coated with special lubricant to avoid cold welding during operation. The function of braids is to guide the flexible harnesses during the bending movements and to protect them against radiation. Two annular end pieces are glued at the extremities of the braid that are coated with a special lubricant to reduce the friction inside the clamping parts. In fact, the lower annular end piece is allowed to rotate inside the corresponding clamping assembly in order to reduce the resistive torques of the flex wiring. This design has been successfully tested on the BB2 breadboard test – the flex cable guiding were subjected to operational lifetime in worst cold environment. The TOM flex cable guidings are shown on the Fig. 5.
SPT-100B thruster delivers 83 mN with a specific impulse of \( \leq 1'600 \) s. The discharged power from the SPT100B is 1'350 W and the thruster is qualified for operation in excess of 9'066 hours.

SPT-100B has flight heritage since 1994 on lot of western programs such as Sesat, Stentor, Astra1K, Inmarsat 4F1\&2\&3, Intelsat10-02, XM5, Mbsat, CBmbsat, Americas8, TerreStar 1\&2, Echostar14, IPStar, YahSat 1A\&1B, KaSat, ViaSat , Sirius6, , Intelsat14, NSS12, NSS14.

SPT-140D thruster delivers up to 290 mN with a specific impulse of 1'850 s. The SPT-140D discharged power is 4500 W and the thruster is qualified for operation in excess of 10’000 hours.

SPT-140D is already qualified and has flight heritage on board of the Eutelsat172B.

The main differences between the two thruster configurations that influence the design are:
- The number of XFCs that are needed;
- The no. of xenon tubes transferred across the mechanism;
- The no. of wires from the EPS transferred across the mechanism;
- The temperature at the Thruster I/F with the thruster mounting plate.

The thruster mass for the two configurations is similar and equals to ~10 kg.

C. TOM design and characteristics

TOM consists of two actuators, a shock damping and a staged thermal control subsystems. Also TOM consists of a hold-down and release mechanism (HDRM) that provides locking of thruster platform to protect TOM from mechanical loads during a launch vehicle flight. The TOM design structure is shown on the Fig. 6, and 7.

TOM provides a thrust vector with rotation in two degrees of freedom in the angular range from -14° to +34° around \( \alpha \)-axis (elevation axis) and from -14° to +14° around \( \beta \)-axis (azimuth axis) including the case when the thruster is operating. TOM angular position is controlled by two actuators, which consist of a 360° redundant stepper motor with a step precision of 0.00205°. Each axis can be rotated with the nominal speed of 0.20°/sec and with the maximum speed of 0.35°/sec. TOM has been qualified for as many as 10’000 rotation cycles in the full angular range and for as many as 60’000 cycles in following angular ranges: 75% cycles in range of ±1°, 20% cycles in range of ±5° and 5% cycles in the full angular range.

HDRM consists of the three support legs. The three support legs holding the thruster support platform contain at the upper end, the G&H separation nut, and at the lower end the hinge and spring to enable the support legs to rotate away from the platform. The G&H separation nut is a non-explosive separation nut for minimum shock separation with significant space heritage and in particular was used on the Mars Global Surveyor and the Mars Pathfinder for antenna and solar panel release. The support leg design ensures the required stiffness and strength to the launch lock system for the random vibration loads and guarantees the release of the HDRM under all thermomechanical loads.

The shock damper system was successfully used on the SMART-1 EPMEC and consists of a silicone elastomer ring, which injected between two rings to provide the damping required for the mounted thrusters. XFC brackets also provide damping the shock to the admissible levels for the XFC modules.

The purpose of the shock damper system is to minimise the transmitted shock and vibration from the spacecraft to the thrusters during the launch phase of the mission. The secondary function is to reduce the heat flux transmitted from the thruster to the spacecraft during operation. Since the Smart-1 program, the material of the shock damping system had been investigated and re-worked regarding to accommodate two different thruster configurations, which
has different mass and moment of inertia. The design of the damper has to maximise the damping characteristics and at the same time ensure that the eigen-frequency of the complete assembly is as high as possible, preferably above the high sine test level of up to 100Hz. To improve the requirements the damping system has been successfully verified by testing on the breadboard test that includes mechanical test, radiation proof test and thermal test.

The breadboard test results show that the damper material is suitable for long operation in orbit during 15 years. However, it should be noted that the strength of the material is only necessary at BOL (Beginning of Life) during the launch phase and during the release of the separation nuts, whose shock generated is up to 2000g.

After that, the material is not subjected to significant loads, but used for heat dissipation from the thrusters. The maximum temperature at the shock damper interface in the worst hot case is 75°C (including all margins). This value is much lower than the maximum temperature at which the damping system was characterised w.r.t. the thermal distortion. Therefore, the required pointing stability of the system is always satisfied.

The lower structure (the drive unit and the support platform assembly) is insulated conductively and radiatively from the thruster plate assembly because of different temperature limits. In order to mitigate the risk of overheating the lower structure, two-staged thermal control system (TCS) had induced in the thruster mounting plate.

First stage of the TCS decoupled the thruster mounting plate and thruster feet by insulation titanium stand-offs to limit the maximum operating temperature of the radiator and the thruster mounting plate. Moreover, in order to avoid the negative effects of solar reflection in the space between the thrusters and the radiator, a MLI blanket had put around the thrusters to cover this space completely.

At the second stage the thruster mounting plate mounts to the shock damping system by titanium stand-offs to the inner ring of the shock damping system to minimise the heat flux transmitted to the actuators. The damping ring provides additional isolation for the actuators.

Radiator for the two types of the thruster system configuration has different radiation effective area because of different hot temperature levels of SPT-140D and SPT-100B thrusters. For EPS-100, the radiator should have a radiator area of at least 0.17 m² to provide simultaneous operation of the two SPT-100B thrusters. Radiator for the SPT-140D is smaller because of the heat flow from the thruster mounting plate to the radiator is about 13W in the worst hot case in order to maintain the thruster interface temperature at 290 °C maximum.

In order to provide radiative insulation of the lower structure, MLI are attached on the naked parts of the TOM lower structure. Due to the wide angular ranges to be performed around both axes, the most natural solution is a set of MLI blankets wrapped-up separately on the lower structure parts.

The active thermal control system consist of the high temperature heaters (one heaters pair (main and redundant) on each SPT and XFC), which attached to the thruster mounting plate and the XFC bracket, and maintain the minimum temperature of the thrusters and XFC modules during the cold periods.

All the TOM functional parts are mounted on the TOM baseplate that have lowest possible mass equalled to 3.5 kg due to using of honeycomb structure and optimization of threaded inserts.

Total TOM mass is 18 kg. Such mass value explained by needs for development of the TOM100 and TOM140 in order to achieve the high performances and to implement the design features, mentioned above.

III. Qualification of ITU100 & ITU140 at EDB Fakel facilities

A. TOM QM qualification test philosophy and results

For qualification purpose, two separate TOM for each thruster system configuration could be produced, but this makes the development process both lengthy and costly. It is therefore essential to optimise the qualification campaign flow to reduce the logistics necessary during testing and to minimise the cost and the resource issues.

Since many of the requirements for the two thruster configurations are similar and the differences do not have a major impact on the design it was decided to build two QM models with common lower structure that can be used to qualify both TOM, and with an exchangeable upper structure, which supports the two EP system configurations. The EP systems, which utilised for the qualification models, are consists of the SPT-140D and the SPT-100B dummies.

Figure 7. Assembled TOM
The QM models have both been subjected to a classical qualification campaign, which will include generally mechanical test, functional test, thermo-vacuum test and lifetime test. During the TOM qualification campaign the upper structures with SPT-140D and SPT-100B dummies had been quickly exchanged at various test stages.

EP system configuration with two SPT-100B dummies represents the worst case of the TOM operation, because additional tubes and EP harnesses have an influence on the stiffness and resistance torque of the mechanism. For this reason, the TOM-100 was subjected to the test.

Breadboard testing provides excellent support during the design process and helps to mitigate issues that could occur downstream in a development and introduce unnecessary delays and extra costs.

TOM qualification campaign shows susceptibility to the environmental mechanical and thermal loads, and demonstrate that the TOM lifetime requirements has been achieved in the most cost effective and quickest way.

B. Manufacturing and qualification test campaign of ITU100 and ITU140

In order to manufacture and qualify the ITU100 and ITU140 with real thrusters, the TOM QM (lower structure) with EP system integration set was sent by RUAG to EDB Fakel. For the ITU qualification campaign EDB Fakel had manufactured the SPT-140D and SPT-100B based thruster systems. The thruster systems for ITU represent a separate sub-assembly performed on a separate jig that provides pipework manufacturing and welding between pipework and the thruster systems elements. This jig simulates pipework routing and fixation interfaces, which should be on the ITU. Two EPS-100 on the jig are shown on the Fig. 8. Another jig was used to transfer the thruster systems on the TOM QM.

The ITU100 and ITU140 were subjected to the qualification test campaign in the scope of the qualification test matrix, shown on the Fig. 9, in order to meet the requirements based on the SMART-OLEV mission and partially on the BepiColombo mission.

In the text below the ITU will mean both configuration as environment test for each ITU is the same with difference in the SPT-140D and the SPT-100B test conditions.

During the vibration test, the ITU was tested in a locked state (i.e. TOM legs were nominally stowed and secured) and was exposed to the full level sine and random loads in accordance with the Fig. 10.

The ITU first eigen-frequency values during the full level sine and random vibration test are more than 75 Hz (e.g., ITU00 had minimum at 89 Hz during the sine vibration test) and compliant with the specification requirements.

Resonance test were performed for each axis before and after the vibration test. The resonance frequency shift didn’t exceed the required values after the vibration test. Conclusion based on the ITU vibration test results:
- no mechanical damages have been observed;
- status of electric circuits is within the requirement limits;
- SPT axis positions (linear and angular) are within required tolerance before and after the ITU vibration test.
ITU thermal vacuum test was performed to validate the operating capability of the thermal control system and resistance of the ITU design elements to cycling thermal loads. The ITU was installed directly (i.e. without any intermediate thermal couplings) on the test stand thermal plate that simulated thermally controlled S/C panel. Surrounded thermal screens were used for simulation of surrounding radiation and boundary conductive thermal conditions similar to the flight conditions. Thermal vacuum test fixture is shown on the Fig. 11.

At the minimum temperature level of the first thermal cycle, a remote release of HDRM legs in the worst case (i.e. ITU in vertical position, 1G force is opposite to release direction for one of the legs) was successfully performed and the release status sensors had shown it. Then at the last eight thermal cycles (at maximum environmental temperature level), the thrusters were operating continuously until reaching a thermal equilibrium in the conditions with the maximum ITU design temperature gradients by means of temperature maintenance of the conductive and radiation interfaces at the minimum level. During the ITU100 TVC two SPT-100B were operated simultaneously at the maximum temperature level beginning from the minimum pre-start temperature level and at the minimal temperature level (i.e. minus 180ºC – «cold start»).

Conclusion based on the ITU thermal vacuum test results:
- the ITU elements temperatures were within the required qualification temperature ranges:
  - at the maximum temperature levels: SPT-140D temperatures were not exceeded 320ºC (see the Fig. 12, (a)), SPT-100B temperatures were not exceeded 210ºC (see the Fig. 12, (b)), the actuators temperature were not exceed 55 ºC (see the Fig. 12, (c)).
  - at the minimum temperature levels: ITU elements temperatures are maintained by heaters automatic operation. SPT-140D temperatures were not exceeded minus 65ºC, SPT-100B temperatures were not exceeded minus 48ºC, the actuators temperature were not exceed minus 40 ºC.
- the SPT-140D and the SPT-100B thrusters firing operation parameters comply with the EDB FAKEL standard requirements.

ITU firing test was performed to validate the SPT-140D and the SPT-100B thrusters parameters and TOM functioning when rotating the thruster platform with the operating SPTs. The thruster platform was rotated at all extreme angular positions with the rotation speed of 0.20 °/s. SPT-100B thruster were operated simultaneously. In the conclusion, the firing operation of the thrusters during the thruster plate rotation has not impact on the TOM systems operation.
The both ITU configuration has passed the qualification test in a full scope with all requirements achievement. The ITU qualification test campaign has confirmed the following:

- the ITU100 and ITU140 designs ensure the resistance to the vibration and thermal loads;
- the ITU ensures the thrusters rotations in two planes round two perpendicular axes: along α-axis in the angular range from minus 14° to plus 14° and along β-axis in the angular range from minus 14° to plus 34°;
- the possibility of the SPT-140D and the SPT-100B thrusters and TOM simultaneous operation has been confirmed;
- as the TOM functional test has shown, TOM parameters has not been degraded despite of the TOM QM were subjected both lifetime test at RUAG and two qualification and two acceptance test campaign at EDB Fakel.

IV. ITU100 & ITU140 applicability with new generation of SPT

ITU100 and ITU140 configurations can be used for general applications on geostationary satellites and provide guaranteed the highest accuracy in orbit control:

- correct thrust vector misalignments with respect to the CoG;
- compensate inaccuracies in manufacturing;
- improve or optimize mission performance;
- provide inclination and eccentricity control for North/South or East/West station keeping of a satellite.

For GEO transfer operations, the ITU in both configuration aims to perform transfer operation at short transfer time, short duration in radiation belts, simple thrust strategy. In the ITU100 two SPT-100B thrusters can be simultaneously operated.

For example, ITU in both configuration can be used in the SMART-OLEV docker platform\(^2\) that is designed to be able to service geosat clients for extending their lifetime on orbit (see the Fig. 14); to dock with the client satellite at its functional end of life, and take over attitude and orbital control and station keeping functions. SMART-OLEV mission will be very useful in terms of remove space garbage by retiring “dead” satellites to a graveyard orbit.

The ITU in the both configurations can be mounted as external units on the bottom or on the side panel of the spacecraft like it was design for the SMART-OLEV platform that shown on the Fig. 15. The Sun incidence on the TOM100 can be at any possible angle between 0° and 90°.

Mentioned above the ITU applicability goals can be supplemented by modifying the parameters involved in the working principles of the thruster. Preliminary conceptual solutions have been put forward, concerning modification of magnetic field, electric field, propellant flow rate and geometry.

So, the new modifications of the SPT-100B and SPT-140D thrusters can be used in the ITU configuration. No delta-qualification is needed because the modified SPT has the same mechanical and thermal interfaced as the SPT-140D and the SPT-100B thrusters.

SPT-100BM is a modification of the SPT-100B thruster. The SPT-100BM thruster has lower plume divergence semi-angle that equals to 30°.\(^3\) A smaller plume divergence assembly of
SPT-100BM will allow for a better configuration of the thruster aboard the SC (see the Fig. 16) – it will be possible to install it at a smaller angle, which will significantly increase its application efficiency. SPT-100BM installation at an angle of 30º, the efficient thrust and specific impulse are increased by 20 %.

The SPT-100BM external appearance is shown on the Fig. 17.

If we take into consideration even higher parameters (by 6–8 %) of an upgraded thruster, its thrust and specific impulse at SC will be increased by ~ 30 % compared with the SPT-100B. At the same time, the thruster operation duration will be decreased by one third.

Parameters stability during the long operation and ability to achieve the total impulse of not less than 3.5 MN·s have been demonstrated by the life test of the modified SPT.

In the EPS-140 the separate supply of xenon to the cathode and anode of the SPT-140D thruster is designed to realize deep throttling of output parameters in a wide power range. Since work in this direction is still underway, in the EPS-140 the SPT-140D thruster can be replaced by the SPT-140, qualified for a Russian and foreign customer, without any delta-qualification (see the Fig. 18). The SPT-140 can operate at several operating modes and has one cathode and, accordingly, one XFC module compared to the SPT-140D, which uses two XFC modules. Thus, the mass of the EPS-140 and the load on the actuators by reducing the number of flexible pipes and cables can be reduced. Also, at the moment, EDB Fakel works to develop the SPT-140M for operation in the range of 6 - 8 kW, which has successfully passed the first verification firing test and is under development of an engineering model. Mechanical interfaces of the SPT-140M thruster correspond to the SPT-140 thruster.

V. Conclusion

Currently two TOM-based thruster units the ITU100 and the ITU140 are developed and successfully qualified at EDB Fakel. The flight representatives of the ITU100 and the ITU140 are presented on the Fig. 19, and 20.

Now ITU100 and ITU140 are ready for application and can be modified by new generation SPT without delta-qualification to reach better performance in orbit control operations and propellant consumption economy strategy.
References

