ELECTRIC PROPULSION THRUSTER POINTING MECHANISM (TPM) FOR EUROSTAR 3000: DESIGN & DEVELOPMENT TEST RESULTS

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Abstract: A new mechanism for pointing of electric thrusters is presented in this paper. This mechanism has been developed for the Alternative Thruster Module Assembly (ATMA) as part of the future extended versions of the commercial telecommunications satellite EUROSTAR-3000 made by the European prime contractor EADS-Astrium. The TPM can support 2 thrusters of up to 6.5 kg single mass (ROS2000®, SPT100, or PPS1350G types). The pointing range is at least a 7° half-cone angle to the center of gravity of the satellite, which is achieved via the two degrees of freedom of the mechanism. The hold-down and release mechanism is part of the equipment. The paper will focus on the design description of the TPM, as well as on attenuation test results achieved with a representative Structural Test Model (STM), life test results achieved on drive unit level, and part of performance test results achieved on the Qualification Life Test Model (QLTM) of the TPM. The qualification of the ATMA and, as part of it, the TPM, is still ongoing and expected to be finished early 2006. An outlook on the development of the next generation thruster pointing mechanism EPPM is given. An overview status on the Alternative Thruster Module Assembly is provided as well.

I.   Introduction

Electric propulsion is an option to be used for orbit control of the geostationary telecommunications satellite EUROSTAR-3000, a platform which was developed in Europe by the prime contractor EADS-Astrium (for details refer to http://www.space.eads.net/subsidiaries/eads-astrium). Two Thruster Module Assemblies (TMA) are mounted to north- and south-wall, respectively, of the spacecraft. The TMA is part of the Plasma Propulsion Subsystem on the spacecraft. The ATMA is developed as alternative to the existing TMA, in order to cope with a wider range of thrusters. The TPM is part of the ATMA, and is based on the successfully flown Ion Thruster Alignment Mechanism (ITAM) for ARTEMIS.[1-4]

Austrian Aerospace (AAE, for details refer to http://www.space.at) has been founded in 1997 as a merger of the two former companies ORS (Österreichische Raumfahrt- und Systemtechnik) and SAE (Schrack Aerospace), and is the largest aerospace company in Austria. AAE has been and is involved in nearly all European space projects and has made significant contributions in the area of on-board mechanics (mechanisms and structures), electronics (digital signal processing), thermal hardware (multi layer insulation) and mechanical

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& electrical ground support equipment. The company is owned by Saab Ericsson Space of Gothenburg, Sweden (SES, for details refer to http://www.space.se).

II. TPM Design Objectives

The TPM has been exclusively developed for pointing of electric thrusters with the following main objectives:

- to support two electric thrusters up to 6.5 kg single mass, including ancillary equipment, during launch and in orbit
- to steer the thrusters around two axes
- to provide a thermal barrier between the thrusters and the spacecraft
- to provide inherently the required nominal canting of 45° (approx.) to the S/C launch axis

III. TPM Design Description

This chapter provides a detailed description of the major mechanism parts and technologies used. The following picture provides a view of the TPM Qualification Live Test Model (QLTM, with sketch of S/C accommodation on right side).
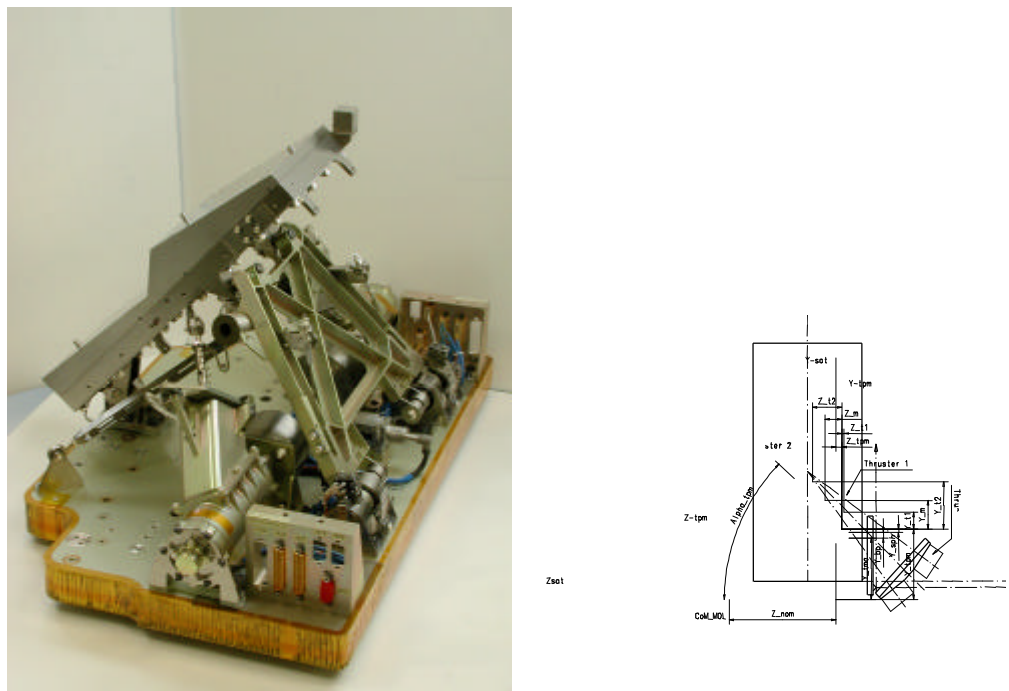

Figure 1. TPM QLTM and location on satellite

A. Kinematics

To ease the understanding of how the mechanism works it is useful to imagine the platform initially free of any support. In this state the platform has six degrees of freedom (DoF), three translations and three rotations. Once the platform is fixed to the S/C by means of the Single Point Hinge (SPH) in such a manner that the translation DoF´s are restrained and only three rotational DoF´s remain. When further one ball jointed strut is added between baseplate and platform the number of rotational degrees of freedom is reduced to two. This means that the platform is able to rotate around two axes, both passing through the SPH. One axis passes through the center of the ball joint of the Transverse Strut Unit (TSU) located on the platform, and the other axis passes through the opposite ball joint of the TSU located on the baseplate (parallel to S/C-x-axis). It can be seen that each additional strut restrains a rotational degree of freedom. Therefore the position in space of the platform is defined when it is supported with one fixed ball joint and three rotating struts. As described above the attitude and position of the platform are determined once the geometric properties of the platform, the length of the struts and the coordinates of the strut endpoints are given. Varying the position of one strut pivot point leads to a

variation of the attitude of the whole platform. This principle is used to adjust the direction of the thrust vector of the platform fixed thrusters.

The mechanism has two of the three struts ending in Drive Units. By driving either of these two spindles the thrust vector can be adjusted to point in any direction within the specified range. The spindles are arranged in such a way that their axis of rotation is parallel to the x-axis. To cover the required range both spindle nuts are able to travel a distance of 70 mm. The attitude of the third, non-adjustable strut was chosen to ensure a symmetric tilting of the platform with respect to the y_M-z_M-plane. This leads to the advantage that both spindles are of the same length.
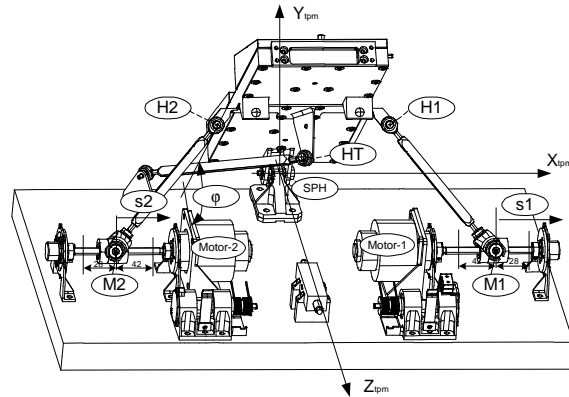

Figure 2. Kinematic Points Definition (TPM sketch only)

B. Passive Attenuation System

Elements providing passive damping are implemented at 7 positions of the mechanism, called SPADD® (Smart Passive Damping Device). These elements provide passive damping of resonances critical for the thrusters mounted to this platform, which are developed due to dynamic coupling between the Hall Effect Thrusters (HET) and the TPM/ATMA structure during random vibration and shock excitation.

SPADD® is a passive and parallel device using specific material and geometry. This technology is integrated in parallel to structures without significantly modifying their stiffness and strength properties. It is able to dissipate vibration energy. In fact, a viscoelastic tape is integrated which dissipates energy upon deformation caused by elastic deformations of the structure. In order to increase its performance, it is associated with specific lever arms. This elements have been designed by the French company ARTEC (see http://www.artec-aerospace.fr). Figure 3 presents a typical example of a SPADD.

Figure 3. Example of SPADD implementation (before gluing)

C. Mobile Platform

The Mobile Thruster Platform (MTB, see fig. 4) is designed to withstand the launch loads and to transfer the loads of the thrusters to the Single Point Hinge and the HDRM during launch, and to the struts during in orbit operation. The platform system consists of the flat surface load carrying structure itself made from Titanium alloy, with SPADD elements implemented, and one combined thruster shim. This shim is specifically tailored to the nominal location of the S/C CoG, thus allowing one baseline TPM design. The MTB has three main functions:

1. Structural: To support the thrusters during launch and operation
2. Thermal: To dissipate thermal energy from the thrusters
3. Attenuation: To attenuate resonance amplifications critical for the HETs

Figure 4. Mobile platform box structure (bottom view)

D. Drive Unit

Two (mirrored) Drive Units (DU, see figure 5) are required for one TPM, in order to operate the two DoF´s of the platform. Each DU consists of the following components, as can be seen in the next figure:
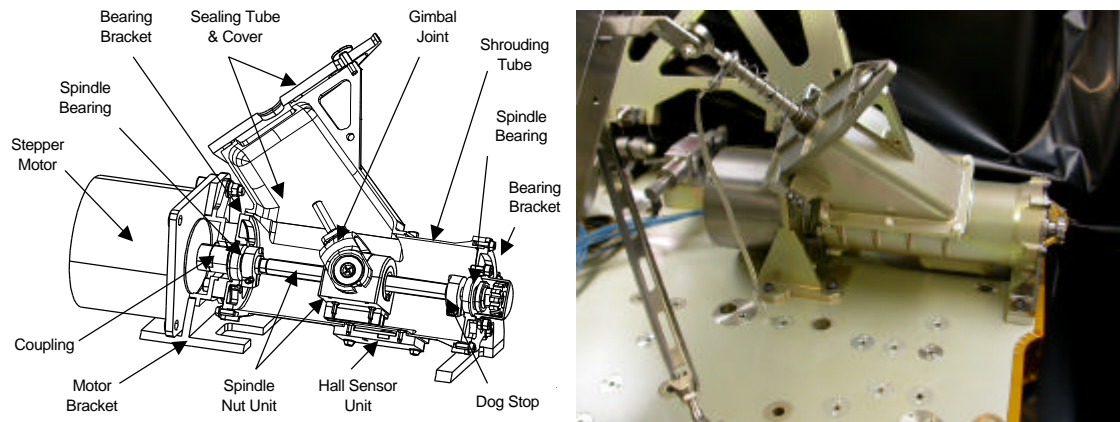

Figure 5. Drive Unit Assembly

A preloaded Recirculating Roller Screw (RRS) has been selected to transform the rotational motion of the stepper motor into linear motion. Mechanical End stops (called Dog-Stops) are provided at each end position of the nut housing to prevent the nut housing from touching the bracket of the Drive Unit.

One pair of spring preloaded angular contact ball bearings with an contact angle of 15° with flanged outer races will be used for support of the RRS. The single bearings are located on both ends of the spindle in a "back-to-back" configuration.

All components used inside the sealed envelope of the Drive Unit are grease lubricated with MAPLUB SH51a (which is a synthetic hydrocarbon oil with PTFE and MoS_2 additives). The DU is sealed via labyrinth seals, and an dedicated evaporation loss analysis has been performed, which confirmed this concept.

A hybrid stepper motor with 24 steps per revolution and redundant windings is selected for the TPM. The worst case moving torque (at min. voltage and max. temperature) is well within the required capacity, including proper margins. Thermistors are incorporated into the redundant windings to allow temperature monitoring.

Redundant Hall Sensor units are incorporated to allow referencing of the DU in the nominal position, and to provide a direction signal upon referencing (high or low, in order to linear drive in the correct direction), because the TPM is operated in open loop.

E. Hold-Down & Release Mechanism

The task of the Hold Down and Release Mechanism (HDRM) for the TPM is to support and hold down the platform during the launch phase and to allow deployment by activating the release actuator, separate the locking cable and release the platform (see figure 6).

After "firing" (non-explosive uses same command as pyro !) of the non-explosive Release Actuator the cable ends are released and stowed by the Release Arms. The Kick springs overcome the adhesion of the Ball-Cup interfaces, and the Support Structure with the Platform I/F Brackets mounted to it rotates away for 60°, actuated by redundant torsion springs, until the structure touches the redundant end-stop and comes to a static end-position after a few oscillations. The Support Structure is latched in its deployed position by means of the actuator springs and the end-stop springs; redundant Micro Switches are indicating the successful release of the HDRM. Platform and HDRM are interfacing via two Ball-Cup Interfaces. The ball is represented by a half-sphere with Ø10 mm mounted to the HDRM Support Structure, the Cup is mounted to the mobile Platform.

A steel cable with 1.6 mm diameter equipped with two turnbuckles for tensioning is fixed to the Release Arms, which are compressing Ball and Cup against each other during launch. The Release Arms are also equipped with redundant Spring Actuators which rotate the arms after release. The cable is routed from one release arm with a Belleville washer assembly for tensioning through the Support Structure via deflection disks down to the Cable Release Actuator, which is mounted separately to the ATMA baseplate, and symmetrically up to the second Ball/Cup I/F.
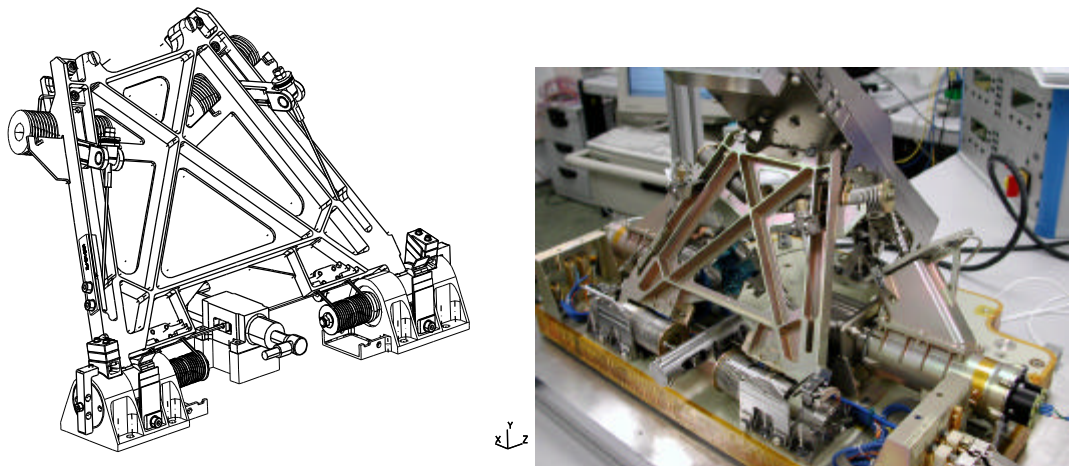
Figure 6. Hold-Down and Release Mechanism Assembly

When the non-explosive release actuator is activated, the cable ends are released and the Release arms free the Ball/Cup interface. The cable has a small Stop Cylinder attached on each side, which allows a movement just until this cylinder reaches the Cable Catcher Bracket mounted to the rotating structure. Therefore the cable is kept save after release. Two sets of double-tandem face-to-face "hard" preloaded Angular Contact Ball Bearings support the Support Structure (i.e. 4 ball bearings on each side), which are also grease lubricated. One Bearing Pair is located on a Sliding Shoe (similar to the Drive Unit) to avoid fighting of the pairs against each other due to thermal distortion.

IV. TPM Performance Test Results

### A. Confidence Life Test on Drive Unit Level

The grease confidence tests performed were twofold:
1. In-vacuo lifetime testing of the Drive Unit (RRS + Bearings) at ambient temperature and in a dedicated test set-up (see fig. 7)

2. In-vacuo parameter testing of the RRS alone at the application temperature extremes of – 25°C and +40°C to get the required data for the DU actuator dimensioning (see fig. 8), performed by ESTL (a division of AEA-Technology, UK)

Results of AAE Life Testing (see fig. 7):
It was required to perform 7 x 42600 cycles for ±0.5 rev at 7 fixed spindle positions and at a distance of 0.41 mm between each other, which yields a total number of 298,900 cycles. The RRS nut loading was 20 N in axial and 24 N in radial direction. A representative actuator was used with 24 steps/rev, driven at 5 Hz step frequency.

There was no significant torque increase over lifetime, and the required duration was successfully passed with no signs of end-of-life. This has been conformed by an strip-down & inspection of the tribological parts (bearings, roller screw).
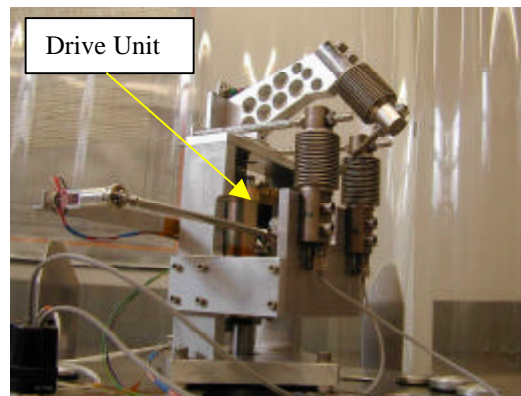
Figure 7. DU life test setup (to be put in TV chamber)

<u>Results of ESTL Roller Screw Parameter Testing:</u>

Measurement of peak and running torque over one cycle (2 revs ccw; 2 revs cw) at speeds of 1, 50 and 100 rpm and –25°C / ambient / 45°C were performed. At the higher speeds of operation examined (50 and 100 rpm) the torques increase appreciably as the temperature decreases below 15°C and achieve their highest values at the lowest temperatures examined (-23°C). In contrast, tests performed at 1 rpm indicate that the torque sensitivity to temperature and viscous effects is much less, indeed the plot of mean torque as a function of temperature is essentially uniform.

The overall conclusion from the tests performed at AAE and ESTL were:
1. The AAE and ESTL tests are considered fully successful and the TPM Drive Unit lubrication system is considered suitable for the lifetime demand of 300,000 cycles and corresponding cycles definition. There was no sign of end-of-life.
2. At low speeds no temperature dependence of the friction torque could be detected for the chosen lubricant grease. However, at higher speeds and cold temperatures viscous torque effects could be seen
3. The ESTL tests showed in general slightly higher torques than those measured by AAE, which is assumed to be caused by the different test set-up design.
4. The strip-down inspection performed on the tested tribological items showed no anomalous wear.

B. STM Vibration & Shock Tests to determine Attenuation Capability

The ATMA assembly will at S/C launch be loaded by dynamic loads. This loads originate from the transmission of the booster vibration trough the launcher and S/C and by the acoustic vibration excitation of the large S/C panels. The direct excitation by acoustic noise plays, due to the moderate size of the TPM and the missing of large free panels, a minor roll. So the dominating vibrations can be simulated by sine and random vibrations transmitted through the S/C I/F. The incoming vibrations excite the structure and are transmitted to the hall thrusters. There is a high sensitivity of the hall thruster against vibrations in some frequency ranges. Vibration excitation in this ranges should be avoided or at least stay on a moderate level.

The analytic prediction of the eigenfrequencies and the correct estimation of the magnitude of the attenuation/damping factors for a mechanism, especially for higher eigenfrequencies is a job that has to be verified by experimental investigations. It was decided to built a structural model (STM) that is mass and stiffness representative for the TPM. The difference to the flight model (FM) is only, that the electromechanical parts (motors, release unit) are replaced by dummy masses and not the original thrusters are used but "elegant" mass dummies.

The initial STM was tested in a lot of configurations (thrusters dummies of ROS2000, SPT100, or PPS1350G types) and it was demonstrated that the TPM STM survived the loads (sine, random and shock) without any problems. The measured eigenfrequencies in general were higher than the predicted ones, which was easily to clarify as the initial FE-Model was "conservative" in that sense not to overestimate analytically the eigenfrequencies. Sources for deviation were identified as the stiffness of the bolted connection of the thruster shims to the mobile plate which showed experimentally to be stiffer than modeled.

However the crucial thing found out was that the attenuation of the mechanism was too low to protect the sensitive thrusters. The solution was to implement SPADD®-elements by ARTEC (see also chapter B). The idea of these elements is to cut the structure in the regions of highest strain-energy density and to bridge the cut by a metal stripe glued by the side-walls with a special viscous adhesive that has good energy dissipating properties. The principal idea is, that the original structure and the modified structure have the same eigenfrequency. In addition to that a small modification was made: the originally two thruster shims were combined to a single shim to shift some eigenfrequencies out of the region critical for the cathodes. After the modification including some tests on sample level the modified STM was again dynamically tested. All important tests to determine for all thruster types the attenuation were repeated and to verify the design the high level test with the ROS2000 (heaviest thruster) were repeated. No random load notching to protect the TPM was requested.

In the critical region for the cathodes (100-300 Hz), the response peaks were reduced drastically, and therefore acceptable for the highly sensitive hall thrusters. The drop of the first eigenfrequency is within an acceptable range.
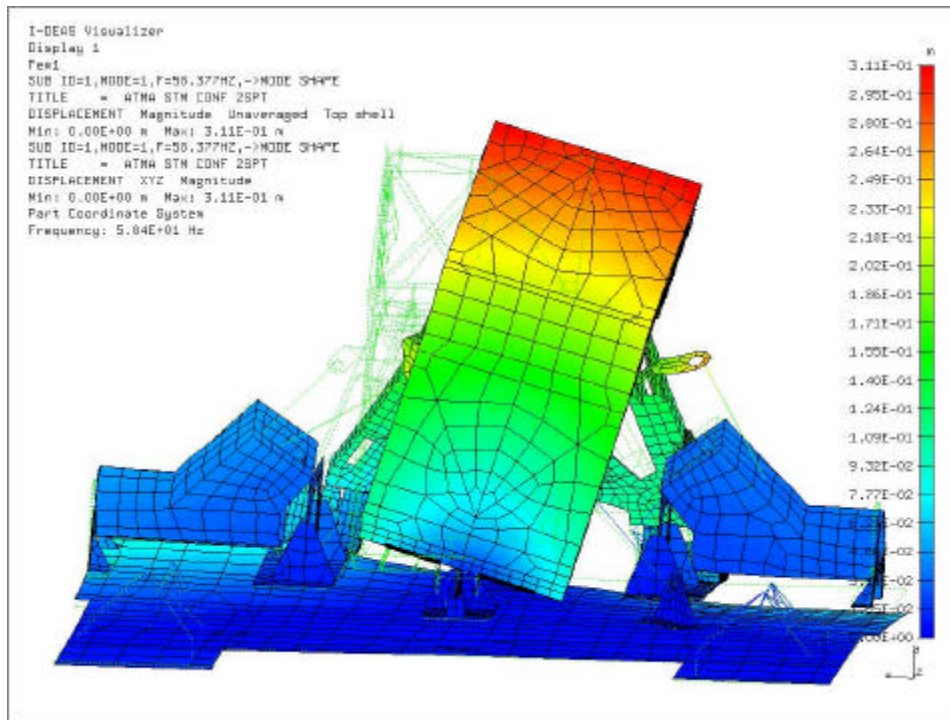
The 29th International Electric Propulsion Conference, Princeton University,
October 31 – November 4, 2005

Figure 11. FE-Plot of 1st EF Mode Shape

C. QLTM Physical Properties Tests

The main physical properties are given below. The data are valid for the TPM mechanism without ATMA baseplate and MLI:

Parameter	Value
Mass	10.35 kg
Over all size (TPM) in stowed configuration	Width x Depth x Hight 595 x 389 x 350 [mm]

D. QLTM Performance Tests

The following tests done on the QLTM so far are the following:

- Check out test: First function check
- Alignment test: Pointing accuracy verification on 3-D Measurement machine
- Workmanship test = Vibration test on mechanism level
- Thermal Vacuum Function Test: Verification of torque margins at qualification temperatures under TV conditions.

The main parameters are given in the table below:

Parameter	Value
Pointing range	Min. 7° half-Cone (see fig 8 for actual range)
Pointing Resolution nominal position	<0.01° / Step
Motion Speed	up to 10 Hz/ nominal 2Hz
Load Capability	10 Nm resistive torque (harness & piping)
Operational Temperature Range	Baseplate –14°C to +92°C, Thruster I/F up to +267°C
Operational Voltage	28V
average Power Consumption	2.27 W at Hot Case 2.92 W at Cold Case
Peak Power Consumption	9.86W at Hot Case 15.7 W at Cold Case

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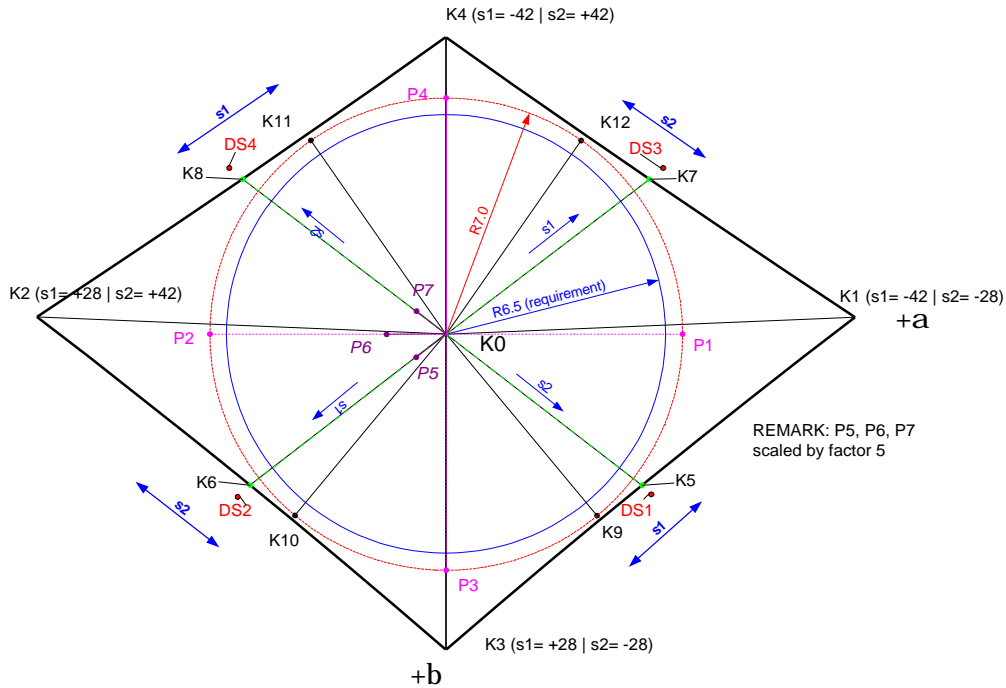*October 31 – November 4, 2005*

Figure 12. TPM Pointing Range

V.   ATMA Overview

A.   Development Approach

Similarly to the Artemis and Stentor programs EADS Astrium selected a pointing mechanism concept combining canting angles and pointing ability for the extension of the Eurostar E3000 missions. The new mechanism had to be compatible with all thrusters in development. This approach resulted in major outlines of the product as described above. Another set of constraints came from the ability imposed on the design to be compatible with the current platform capabilities, that to say mainly to be compatible with the interface of the currently flying generation.

A careful review of the requirements and capabilities of the partners involved in the development resulted in a work shared approach. Most of the mechanism sizing was undertaken by AAE while coupled aspects with the supporting satellites were undertaken by EADS Astrium as they were requiring a deeper knowledge and fine modeling of the mechanism surroundings. EADS Astrium also fed the mechanism study with interface considerations on all the interface data regarding the thrusters and the ancillary numerous components. The supporting baseplate onto which the TPM will be assembled or the surrounding Multi Layer Insulation fell also under EADS Astrium responsibility as it plays an integral part of the spacecraft.

EADS Astrium contributed largely to the STM test campaigns by providing test facilities and exhaustive analytical tools which allowed a fairy comprehensive comparison with the spacecraft behavior.

B.   Current Status

Having finalized the design phase with promising life test results and dynamic responses from the SPADD® incorporating design the program entered in the qualification phase. While most of this phase consists in testing the ATMA with adequate margins over life, vibration or thermal requirements, this phase of the program has also been aimed at implementing an industrial scheme which can be easily reproduced for flight models.

The qualification life test model (QLTM) of the TPM was assembled by AAE according to flight model procedures on a flight baseplate, underwent functional checks before delivery to EADS Astrium including actuation in thermal conditions. It was populated with harness, tubing and representative dummies of the most costly elements (thrusters, filter units and flow controllers) from thermal and mechanical point of views. This phase is now achieved and the QLTM ATMA has gone through its TRR. It shall soon be mechanically and thermally tested. Performances will be checked all along the qualification process including pointing capabilities, leak-tightness of the connections and electrical isolations or continuities. Release tests will be performed before finally taking the ATMA into a life test at thermal extremes.

C. Future Steps

The above sequence shall provide a new thruster module assembly compatible with extended range of thrusters and set of requirements. Introduction on the spacecraft should be done in a timely manner depending on the market demand for electric propulsion. The limited impact on the spacecraft interfaces and the very detailed qualification plan should allow for a protoflight model introduction, possibly as early as 2006.

VI. Outlook

AAE is also under contract to ESA for the next generation thruster pointing mechanism, now called EPPM (Electric Propulsion Thruster Pointing Mechanism). This mechanism is foreseen to cope with the new generation of high power thrusters (up to 5 kW), like the gridded ion thrusters T6 (QinetiQ) and RIT-22 (EADS-ST), or the hall effect thruster PPS5000® (Snecma). The project has started, and currently all applicable requirements are evaluated and design concept trades performed. Target applications of the EPPM are the extended versions of Alphabus, and the solar electric propulsion system of Bepi-Colombo.

From the current point of view, the most promising concept is one which directly mounts the thrusters to the S/C structure, in order to avoid excessive amplification, the EPPM mechanism may look like shown in the following picture. However, the design concept trade is still to be made, and confirmed as soon as final requirements from the target applications are available.
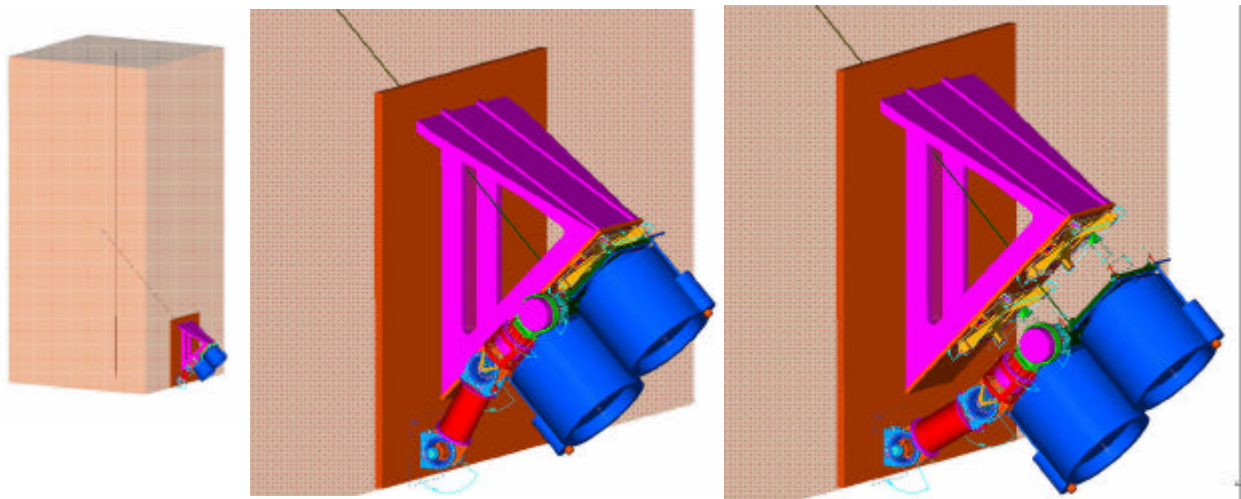
Figure 10. EPPM candidate concept sketch (status: September 2005)

This concept maintains the nominal thruster position in stowed configuration, and can be scaled to the required pointing range via appropriate selection of the geometry. Note that in this case the mechanism structure is no more between S/C and thrusters, thus allowing a much stiffer connection ("thrusters hard mounted to S/C"), which also thermally disconnects the thrusters from the mechanism actuators.

VII. Conclusion

The alternative Thruster Pointing Mechanism for Eurostar-3000 has been successfully development tested, and is currently under qualification at the customer. Upon finalization of this project, a valid alternative to the currently used thruster pointing system is available.

Acknowledgements
We gratefully acknowledge the joint effort of EADS-ASTRIUM and ESA for the continued support of the TPM qualification for Eurostar-3000.

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