RIT-3.5: A Radio Frequency Mini Ion Engine According to the Propulsion Requirements of the Next Generation Gravity Missions “NGGM”

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ABSTRACT:

The Earth Observation missions using gravitational mapping of the planet are getting more and more a indispensable tool for monitoring the dynamics of our planet. The “Next-Generation Gravity Mission” (NGGM) concept, under study at the European Space Agency (ESA), will make use of the Low-Low Satellite-to-Satellite Tracking technique to monitor the temporal variations of the Earth gravity field over a long time span. One of the enabling technologies for the realization of the NGGM is the micro propulsion system. Miniature radio frequency ion thrusters have been identified as candidate low noise actuators for the NGGM satellites. The precise, low and variable thrust provided by this type of thruster shall permit the lateral drag forces on the satellites to be compensated and also laser beam pointing control to the accuracy required for the mission. Granted of an ESA contract within the basic Technology Research Programme (TRP), an engineering model of such a thruster was designed, constructed and tested in TransMIT GmbH in Germany. The paper discusses the design specifications and delivers the test results

ABBREVIATIONS AND ACRONYMS:

NGGM	Next Generation Gravity Mission
ESA	European Space Agency
TRP	Technology Research Programme
APCON	Apcon AeroSpace & Defence GmbH
GRACE	Gravity Recovery and Climate Experiment
GOCE	Gravity field and steady- state Ocean Circulation Explorer
SST	Satellite-to-Satellite Tracking
ll-SST	Low-Low Satellite-to-Satellite Tracking
Isp	Specific Impulse
AOCS	Attitude and Orbit Control System
RIT	Radio Frequency Ion Thruster
GIE	Gridded Ion Engine
RF	Radio Frequency
RFG	Radio Frequency Generator
PSCU	Power Supply Control Unit
PPU	Power Processing Unit
FCU	Flow Control Unit

1. INTRODUCTION

The next generation gravity mission is a mission based on fine attitude control and positioning of two satellites flying a formation flight. The necessary maneuvers for this mission impose strict

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requirements on controllability of the propulsion system of such satellites. Apart from the propulsive functions for the satellite-satellite tracking, the thrusters shall also compensate the atmospheric drag, as the mission measurement precision would profit from the flying in low attitudes, where the atmospheric drag can be a determining factor. The atmospheric drag in the NGGM mission relevant altitudes can be estimated to be between few hundred micro-Newtons to few mili-Newtons. As the maneuvers of satellite-satellite tracking require precise thrusts in the few ten micro-Newton regime, a very high thrust dynamics of a factor 50 between the minimum thrust and the maximum thrust is required. This high dynamics together with the requirement for low power consumption, based on the fact that the satellite flying in very Low earth orbit cannot have large solar sells, and the very high life time of the mission (up to 7 years) face the thruster developers to a hard challenges.

Transmit GmbH, together with Apcon AeroSpace & Defence GmbH in Munich as partners, started the development of a thruster specially designed to fulfill the propulsion requirements of the NGGM. In this development, TransMIT was responsible for the plasma, EM and performance modeling as well as designing of the thruster and Apcon was responsible for the production and the development of a Radio Frequency Generator (RFG).

This paper presents the latest results of the development and shows the test results.

2. NGGM CONCEPT

Following the selection in 1999 of the first Earth Explorer Core mission, GOCE [1], the European Space Agency has initiated in 2003 activities on future gravity missions with a study on observation techniques for solid Earth missions [2], and has continued this effort in recent years through several system studies and technology development activities. In particular, the new science goals were derived within the study [2], which also covered the major characteristics of the sensor systems and defined scenarios with mission outlines and anticipated performance for the determination of the gravity field, improving upon the GRACE (Gravity Recovery and Climate Experiment) [3] and GOCE (Gravity field and steady- state Ocean Circulation Explorer) [1] missions. The most promising identified scenarios addressed a Gradiometer mission, targeting the higher spatial frequencies of the spherical harmonics, and a Satellite-to-Satellite Tracking (SST) mission for the determination of the low spatial frequencies to higher accuracies than its predecessors.

The following system studies have suggested that such a mission ought to be based on Low-Low Satellite-to-Satellite Tracking (ll-SST). This technique exploits the satellites themselves as “proof masses” immersed in the Earth gravity field (as shown in Fig. 1). The satellites fly in a loose formation in which they are free to move under the action of the gravity field within a measurement band with a typical lower bound <1 mHz. Since the altitude of the satellite must be low (around 350 km or less) to increase the sensitivity to the higher harmonics of the Earth gravity field, the relative motion between the satellites will be perturbed by aerodynamic forces (i.e. air drag) too. The distance variation between their centres of mass (produced by both gravitational and non-gravitational forces together) is measured at high resolution by a distance metrology set-up. The achievement of the mission objectives calls for a relative error in the distance measurement of the order of 10-13 m/√Hz, namely 10 nm/√Hz for a typical inter-satellite distance of 100 km.

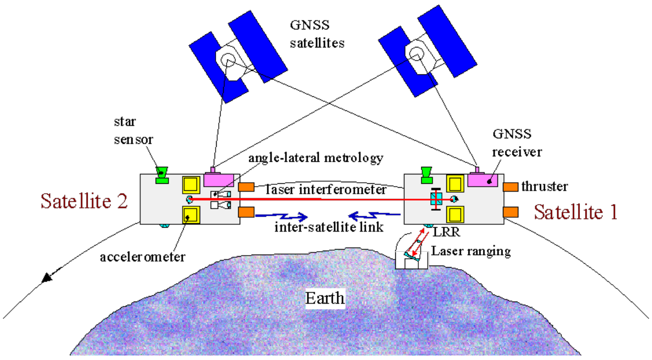

Figure 1. ll-SST principle for the Next Generation Gravity Mission (courtesy by TAS Turin, Italy)

All these activities have received precious inputs from the in-flight lessons learned either from GOCE or the US-German mission GRACE. Others activities were initiated to improve the technology of the Attitude and Orbit Control System (AOCS, e.g. tests on magnetic bearing reaction wheels and miniaturized ion thrusters), this area being clearly a driver for the mission design.

The objectives of a “Next-Generation Gravity Mission” (NGGM), as identified in the science workshops held in 2007 [4] and 2009[5], are to provide the temporal variations of the Earth’s gravity field over a time span of several years with high spatial resolution (i.e. ~100 km, comparable to that provided by GOCE) and higher temporal resolution than GRACE, which is limited to ~1 month intervals between successive gravity field maps. Such a mission will significantly improve our understanding of mass change of ice sheets and glaciers, continental water cycles, ocean masses dynamics, solid-earth deformations and other geophysical phenomena through observations of the mass transportation within the Earth system, as derived from the consequent temporal variations of the gravity field.

From this basis, in 2009 the “Assessment of a Next Generation Gravity Mission for Monitoring the Variations of the Earth’s Gravity” [6-7] has been run through two parallel studies, one led by ThalesAlenia Space (Turin, Italy) and another one by Astrium GmbH (Friedrichshafen, Germany). Several mission aspects were analysed, covering orbit geometry, altitude, inter-satellite distance, number and accommodation of sensing instruments (i.e. accelerometers) per satellite, laser ranging technology, satellite formation and lifetime. After the system studies, further technological development studies have been started within the ESA Technology Research Programme, concerning the laser metrology design (i.e. laser head and laser stabilization unit), miniaturized Field Emission Electric Propulsion (FEEP) and miniaturised Radio-frequency Ion Thruster (mini-RIT).

The low-thrust electric propulsion with variable thrust is one of the key technologies for accomplishing the challenging mission requirements of the NGGM. In particular, it shall allow:

- satellite orbit maintenance;
- satellite loose formation control;
- implementation of the individual drag-free control; attitude control of each satellite;
- laser beam pointing control.

3. NGGM REQUIREMENTS

The future Next-Generation Gravity Mission concept, as well as other Earth Observation missions and Science missions, will require fine attitude and orbit control by means of low-noise force actuators. Such missions will benefit and, in some case, will be enabled by electric propulsion systems capable of combining high specific impulse and ultra fine controllability. For the broad range of applications, more than one thruster typology is required, depending also on the satellite configuration and on the type of formation geometry.

For NGGM, in case of the simplest in-line formation, in which the satellites chase each other along the same orbit and experience a main drag force mainly along the velocity vector, the need of two types of thrusters has been identified (main thrusters and miniaturized thrusters for lateral controllability, in brief “lateral” ones). The criticalities of these thrusters are the thrust dynamic range (a value > 40 is needed to cope with the large variation of the drag forces encountered in a long duration mission, especially in periods of high solar activity), the specific power for minimizing the solar panel surface, the specific impulse for reducing propellant consumption (the current estimate leads to about 50 kg of Xenon for a 10 year mission) and the lifetime.

Tab. 1 summarizes the propulsion requirements for the lateral thrusters as identified in the last system studies [6-7].

Table 1. Propulsion requirements for NGGM

Parameter	Unit	Collinear Lateral Thrusters
Minimum Thrust	mN	0.05 (0*)
Maximum Thrust	mN	< 3
Thrust Resolution	µN	0.5
Thrust Noise		<1µN/√Hz above 0.08Hz
Rise/Fall Time	ms	< 50
Slew Rate	mN/s	> 0.5
Update command rate	Hz	10
Thrust non linearity		< 2%
Lifetime	yr	> 10
Specific Power	W/mN	< 40
* Thrust has to be turned off completely if thruster is not operating		

4. THRUSTER MODELLING AND DESIGN

In order to simulate the plasma, electromagnetic and thermal aspects of the thruster model for the comprehensive radio frequency (RF) gridded – ion thruster, a modelling was developed [9] in order to define generic thruster parameters and its geometry. This was achieved by representing different areas of physics by a different sub–model: 2D ion optics, 3D neutral gas, Boltzmann electron transport, 0D plasma, RF circuit, 2D electromagnetic and 3D thermal. All the sub–models were coupled together for a consistent solution. Such a holistic approach, apart from other parameters, enables one to determine the power transferred to the plasma, the coupling between the plasma and the coil, the extraction beam current and ultimately the thruster efficiency. Therefore, a thorough optimization analysis can be performed. Furthermore, the thruster performance can be simulated as in the actual experiment where all different parameters/physics are connected. By comparing the RIT 3.5 experimental data to the model results, it was shown that the model can predict the input power and current to the radio – frequency generator at different operational conditions with an error less than 10%, similar accuracy was achieved in predicting the temperature distribution.

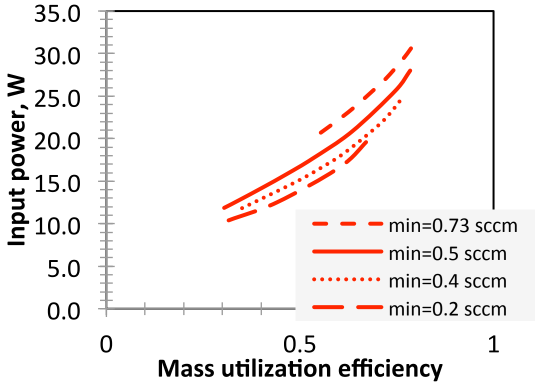

Figure 2. Input power as a function of the mass utilization efficiency for different mass flow rates.

Fig. 2 shows the simulated thruster performance when the input mass flow rate $\dot{m}_{in}$is kept constant, but the input power is varied to achieve a particular mass utilization efficiency. This means that as the input power to the radio–frequency generator is increased for the same mass flow rate, the ion density rises and, thus, the beam current increases, resulting in a higher mass utilization efficiency. Nevertheless, the required power increases exponentially with increasing mass utilization efficiency.

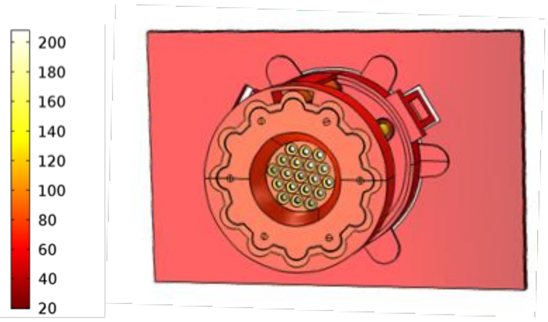

Figure 3. Temperature distribution in RIT 3.5 thruster for 18 W of input power without plasma. Temperatures are in ℃; the thruster outer case is hidden for the visualization purposes

A thermal model was developed to distinguish the critical components in the RIT 3.5 design. Fig. 3 depicts the simulated temperature distribution inside the RIT 3.5 thruster at 18 W of input power without the plasma. The model was cross checked with the results of the test. In the thruster nine thermosensors were installed, which register the temperature of the different components in the thruster. The thruster can be operated to its maximum thrust without any thermal problems.

5. EXPERIMENTAL RESULTS

In the frame of the project, an extensive experimental program divided in two sequences of characterisation and endurance tests was foreseen.

Characterisation tests included performance mapping, thrust range tests, thrust resolution and thrust noise qualification and thrust fall/rise time definition. Endurance test should include 1000 h of direct firing of the thruster and will start in the middle of May 2016.

In order to study the facility effects, a performance mapping was done in two vacuum test facilities:

- R2D2 vacuum test facility of TransMIT GmbH depicted in Fig. 4. This facility comprises two volumes – main chamber and hatch with total volume 4.5 m^3 and total pumping capacity of 24 000 l/s.

Figure 4. R2D2 test facility

- Vacuum test facility of University of Southampton depicted in Fig. 5. This facility consists of a main and a loading chamber as well, and has a total volume of 7 m^3 and total pumping capacity of 34 000 l/s.

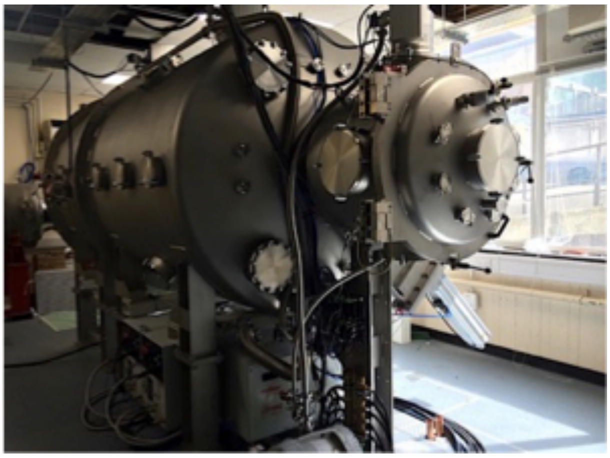

Figure 5. Electric Propulsion vacuum test facility of the University of Southamton

The most challenging part of the thruster requirements for NGGM was the very large dynamic range of the thrust which had to be demonstrated in the frame of the characterisation test campaign. The minimum thrust was required to be around 50µN and the maximum not less than 2000µN. The Fig. 6 shows the results of the thrust range achieved in the frame of such tests: power consumption of the thruster (including the losses in power supplies) for different thrust levels.

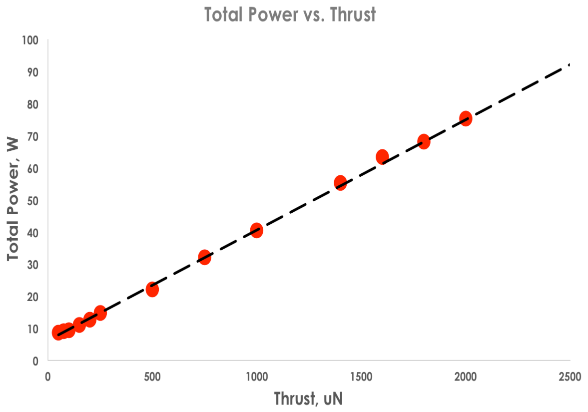

Figure 6. The power consumption of the thruster (including the losses in power supplies) for different thrust levels between 45µN-2500µN

As can be seen, a minimum thrust of 45µN and a maximum thrust of 2500µN were achieved. The power consumption at maximum thrust is around 90 Watts, which allows a power to thrust ratio below 40W/mN at bus level.

Difference in the power consumtion at the same thrust levels for the thruster working in both test facilities was shown to be about 3%.

Fig. 7 shows the variation of the thruster Isp for different thrusts. An Isp between 300s to 3800s depending on the thrust was achieved.

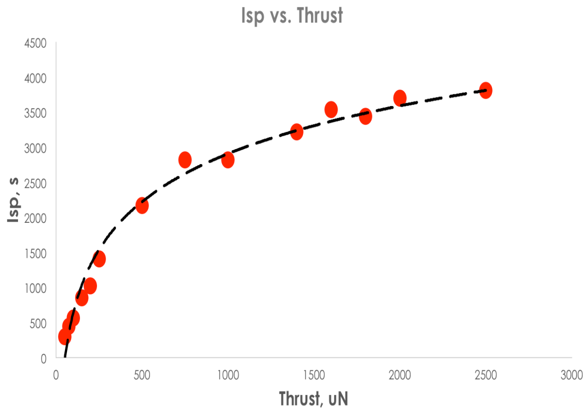

Figure 7. The Isp of the thruster for different thrust levels between 45µN-2500µN

The thrust stepping and resolution is tested for different thrust levels. A stepping of under 0.2µN could be achieved. Fig. 8 shows the example of thrust stepping for 2mN thrust.

Requirements for thrust noise and thrust raise/fall time were also shown to be satisfactory for NGGM mission.

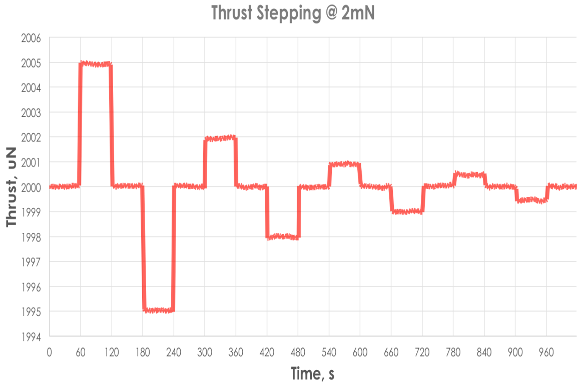

Figure 8. The thrust stepping by 2mN thrust

6. SPECIAL CONSIDERATIONS AND CONCLUSION

A Radio Frequency Mini Ion Engine RIT3.5 was developed according to the Propulsion Requirements of the Next Generation Gravity Missions. Detailed Characterization test campaign confirmed compliance of the thruster to the mission profile. Upcoming Endurance test campaign should demonstrate whether lifetime of RIT3.5 is as well relevant to the requirements. Fig. 9 depicts the thruster.

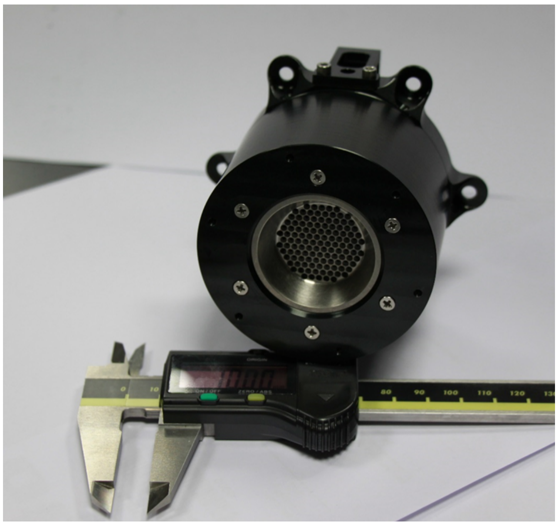

Figure 9. RIT 3.5 developed by TransMIT GmbH

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