***Applications of Microthrusters on Astrophysics Missions with Demanding Jitter Requirements – a White Paper***

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**1. KEY ISSUE AND OVERVIEW OF IMPACT ON THE FIELD**

**Introduction**

Pointing repeatability and stability (jitter) requirements are key for large space telescope missions of the future. For example, managing jitter is essential to being able to “image” planets on future exo-planet coronagraph missions. Jitter requirements for missions in this class are difficult to meet with current reaction wheel-based architectures. The reaction wheels themselves are typically the largest pointing disturbance on the spacecraft.

Thrusters capable of thrust forces in the micronewton range (referred to as microthrusters or micro-Newton thrusters) have been developed to support the Laser Interferometer Space Antenna (LISA) mission, which requires drag-free control to place a test mass in near-perfect free fall [1]. Beyond the LISA application, microthrusters could be used either as a substitute for reaction wheels or as a supplement to wheels for fine pointing control. Used in this fashion, microthrusters have potential for reducing the cost and technical risks of achieving demanding pointing stability performance on observatory-class missions.

The trend on Astrophysics observatory missions is toward tighter and more demanding pointing stability requirements. The NASA Engineering and Safety Center (NESC) conducted a preliminary study in 2017 of the use of microthrusters for fine pointing, and is currently engaged in an assessment of the benefits of microthrusters in comparison to reaction wheels for future observatory missions with tight fine-pointing requirements. The NESC assessment team would look forward to the possibility of presenting the status and / or results of this study to the Astrophysics Decadal Survey.

**Jitter and Microvibration**

Jitter is short-period or high-frequency motion relative to the integration or exposure time for an observation [2][3][4]. Jitter can be caused by microvibrations generated by internal mechanisms or mechanical devices. These typically include internal rotating mechanisms such as reaction wheels and/or momentum wheels, and cyclic devices as cryocoolers and cryopumps. Devices which are internal to science payloads such as scanning mirrors, steering mirrors, and filter wheel mechanisms can also be sources of microvibration. Disturbances can also arise from the use of high gain antenna and / or solar array drive mechanisms, appendage gimbal drives/pointing mechanisms, and attitude control/momentum dumping thrusters. Propellant sloshing and control-structures interactions may also contribute to the spacecraft’s internal disturbance environment and can potentially excite microvibration at a critical payload instrument location.

To meet tight pointing stability / jitter requirements, the spacecraft’s design must protect against degraded output performance of the payload’s optical sensors caused by the transmission of spacecraft internal mechanical disturbances from their source through the vehicle’s structure to the sensing elements in the payload instruments. These optical degradations typically occur due to low-energy excitations of the spacecraft system’s structural modes of vibration at high frequencies (relative to the spacecraft’s attitude control bandwidth), that often possess very low inherent damping. For the majority of NASA’s science missions the microvibration solution is focused on the modeling, analysis, and test of precision optical-mechanical space observatory systems (i.e., a spacecraft bus supporting a science instrument payload) but microvibration can also impact precision pointing of steerable high gain antennas.

Mitigating jitter has in the past proved costly to projects, necessitating the formation of dedicated teams of specialists. More challenging jitter requirements require higher model fidelity, more detailed error budgets and more attention to identification of error sources. Microvibration is a system level problem. The tougher the requirements are, the stronger the inter-subsystem dependencies are, and the harder it is to solve the problem inside a single subsystem. The team working on the microvibration requirements can drive the system level design, architecture, and testing and thus cost and schedule. Table 1 (taken from [2]) shows how increasingly demanding pointing stability requirements can drive design decisions and complexity.

Table 1: Rules of Thumb for Design of Fine-Pointing Spacecraft



Passive mitigation measures are generally preferable to active jitter suppression. These can include avoiding microvibration-producing events during science observations when possible, or momentum management of reaction wheels to avoid certain wheel speed ranges and problem structural modes.

If passive measures are not sufficient to meet the requirement, measures can be taken to improve the performance of microvibration sources. Balancing of reaction wheels can be improved. The frequency content of forcing functions of other input sources can be changed to avoid problem modes. Or problem modes can be “shifted” in frequency by “tailoring” structural dynamics, for example by adding isolation or stiffness control at critical interfaces. Adjustable / swappable structural mount components can be added at critical interfaces to “tune” jitter modes, or tuning masses or mass dampers can be added at critical response areas. The more difficult the jitter requirement is to meet, the more complex the implementation of a solution can become, increasing both cost and technical risk.

Over the last few decades, pointing stability / jitter requirements for Astrophysics missions have become more demanding as the goals and objectives of the Astrophysics program have become more ambitious. A comparison of a few example missions is shown in Figure 1.

Figure 1: Example Observatory Missions and Jitter Requirements



This trend is expected to continue. Pointing stability requirements for the four Astrophysics mission concepts studies currently in progress (HABEX, LUVOIR, OST, and Lynx) all fall in the range shown in the last row of Table 1, essentially challenging the current state of the art. Because reaction wheels can be a significant and sometimes dominant source of microvibration, finding a substitute control actuator which can meet the requirements of a fine-pointing control system and which produces significantly less disturbance is highly desirable. Microthrusters show potential to fill this need.

**Microthrusters**

Microthrusters come in different varieties, using different types of propellant:

* **Cold-gas** thrusters
* **Colloidal** thrusters are a type of electrospray thrusters that apply a high electric potential difference to charged liquid at the end of a hollow needle in such a way that a stream of tiny, charged droplets is emitted generating thrust.
* **FEEP** **(Field Emission Electric Propulsion)** thrusters are another type of electrospray using liquid metal as a propellant and emitting metallic ions.
* **PPT (Pulsed Plasma Thrusters)** use Teflon propellant, discharging a capacitor to achieve thrust

PPTs were the first form of electropropulsion to fly in space, on the Soviet Zond 2 and Zond 3 probes starting in 1964. NASA’s Earth Observer-1 (EO-1) demonstrated the ability to perform roll control for high-resolution imaging with PPT’s, and also demonstrated that electromagnetic interference from the pulsed plasma did not affect other spacecraft systems.

Cold gas microthrusters designed by Leonardo S.p.A (formerly Finmeccanica) have been used for attitude control and fine pointing on three recent European Space Agency (ESA) missions: Microscope [5], ST7 / LISA Pathfinder [1][6], and Gaia [7].

Gaia was the first of the three missions to launch (in December, 2013). Gaia used a set of 12 cold-gas microthrusters for fine attitude pointing and spin rate management (see [8]). The cold-gas microthrusters on Gaia used high-pressure nitrogen propellant to generate very small impulses over a thrust range of 1-500 Micro-Newtons.

The Microscope mission, the third to use cold-gas microthrusters, launched on 4/25/16 and was decommissioned in October 2018 after completion of its science objectives. Microscope employed a Drag-Free Attitude Control System (DFACS), that used a double-redundant primary and backup set of four cold-gas microthrusters (sixteen total) to "fly" the satellite around the test masses [5] [9].

ESA’s LISA Pathfinder (LPF) mission launched 12/3/15 and operated until July 17, 2017 when it was decommissioned. The primary purpose of LPF was to validate key elements of the measurement concept for LISA, principally drag-free propulsion. LISA’s Drag-Free Propulsion System counteracts the disturbance forces and torques applied on the spacecraft in order to maintain the free-floating (or "free-fall") conditions on the science payload’s enclosed master test proof mass.

LPF demonstrated two microthruster systems. One used the Leonardo cold-gas microthrusters based upon those originally developed for the Gaia mission, and was part of ESA’s “LISA Technology Package” (LTP). The second used colloidal microthrusters developed by Busek Co., Inc. under NASA sponsorship as part of NASA’s “Disturbance Reduction System” (DRS) [1].

**Benefits of Microthrusters**

Retiring reaction wheels allows retiring isolation and other mitigation approaches discussed above involving modifications or adaptations of the structural design to avoid certain structural modes. This reduces the associated system engineering effort and cost, and affords structural designers more flexibility.

It is possible to envision the use of microthrusters in several operating scenarios:

**1. Reaction wheels are used for large slews, but are spun down during science observations, with microthrusters used for fine-pointing.** Any need to isolate the reaction wheels is eliminated because the wheels are shut down during fine-pointing.

**2. Traditional RCS thrusters are used for large slews, with microthrusters used for fine pointing.** HABEX is currently baselining this architecture.

**3. Reaction wheels are used for large slews, with frequent large slews required, prohibiting the spinning down of the wheels. Microthrusters are used for momentum unloading of the wheels, which could occur continuously.** This allows the use of smaller wheels (sized for slews only and not the buildup of solar pressure), and restricting the wheels to a desired (“quiet”) speed range. There is no need to interrupt science observation periods for momentum unloading of the reaction wheels since they are unloaded continuously. Also there is no need for a traditional hydrazine RCS thruster system to unload the wheels since the microthrusters are used for that purpose. This architecture could prove suitable for OST, which has an operational mode requiring frequent slews exceeding the control authority of microthrusters.

The trade between 1. and 2. above depends on whether the mass of propellant required for large slews on thrusters is less than the mass of the reaction wheel system, as well as other factors.

**2. STRATEGIC PLAN**

**NESC assessment and application to future missions**

The NESC conducted a preliminary feasibility study in 2017 on benefits of cold-gas microthrusters for fine-pointing control in comparison to reaction wheels, and is now engaged in a higher-fidelity follow-on assessment of those benefits entitled “Micro-Thrusters for Low-Jitter Space Observatory Precision Attitude Control.”

In the 2017 preliminary study, low-fidelity, rigid-body models of the WFIRST and Microscope spacecraft were built in a simulation, and fine-pointing control was simulated using cold-gas microthrusters and reaction wheels (operating separately). The simulation results clearly showed the advantages of microthrusters over wheels, but the fidelity of the simulation left important questions unanswered.

The current NESC assessment expands on this preliminary study, improving the fidelity of the simulation in several ways.

* Spacecraft flexible-mode modeling is added for two example spacecraft (one a “barrel-shaped telescope” based on WFIRST, the other based on the LUVOIR shape), allowing the simulation to reflect structural elastic amplification of disturbances by both reaction wheels and microthrusters
* Reaction wheel disturbances are modeled at higher fidelity, adding several effects not modeled in the preliminary study
* The simulation allows operation of microthrusters and reaction wheels simultaneously, including the transition from wheels to micothrusters
* Modeling of colloidal thrusters is added to the simulation, allowing investigation of both colloidal and cold-gas thrusters in comparison to reaction wheels.

In addition, fortuitous timing allows the NESC assessment to collaborate with LISA by leveraging its testing of a Busek thruster at JPL to extend the model of colloidal thruster disturbances to higher frequencies. The colloidal thruster system flown on LISA Pathfinder was a single-string system. This is considered TRL5 for LISA, which plans to implement a fully redundant system. LISA continues to develop the colloidal microthruster system with plans to achieve TRL6 by 2023. This includes testing a fully redundant thruster string (valves and flow control) in FY19. An enhanced colloidal thruster disturbance model at frequencies of up to 1000 Hz will be built from this test data and incorporated into our simulation.

The simulation will be used to examine all the use cases described above. The results of those simulation exercises and conclusions drawn will be documented in a final report.

This assessment could show a pathway to reducing the cost and risk of satisfying demanding pointing stability requirements for some missions, by using microthrusters instead of isolation systems and other complex solutions required in some cases with reaction wheels.

Following the conclusion of the on-going microthruster assessment the NESC envisions several potential follow-on activities. One possible follow-on activity will be the evaluation of emerging microthruster technologies. The NESC recognizes the wide system trade space to be explored and will likely initiate a number of detailed system trade studies as described below.

**Design trades for future missions**

Mass Trade: study microthrusters propellant mass versus the combined mass of reaction wheels and their isolation systems for various precision observatory attitude control system architectures of interest.

System Complexity/Fault Tolerance Trade: study of various potential observatory precision attitude control system architectures in terms of their inherent complexity, implementation complexities, and fault tolerance. It is envisioned that systems incorporating both large reaction wheels for large angle observatory agility and smaller ‘vernier’ reaction wheels for precision pointing as well as microthrusters for reaction wheel unloading will be evaluated.

System Cost: study microthruster system development & engineering costs versus the cost of developing reaction wheels/isolation systems. These analyses will include the cost impact associated with system complexity in the sense of risk mitigation costs, the system implementation degree of difficulty and system fault tolerance.

**3. ORGANIZATION, PARTNERSHIPS, AND CURRENT STATUS (not applicable)**

**4. SCHEDULE**

The NESC assessment will be completed at the end of CY2019.

LISA is funding development of the Busek colloid microthrusters to TRL 6 by 2023.

**5. COST ESTIMATES (not applicable)**

6. ACKNOWLEDGEMENT

The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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