On orbit validation of solar sailing control laws with thin-film spacecraft

By Michael JOHNSON[1,2,3,4], Julie MCCANN[1], Mathew SANTER[3], Hexi BAOYIN[4] and Shengping GONG[4]

[1] *Department of Computing, Imperial College London, London, United Kingdom*
[2] *PocketSpacecraft.com (USA), Pasadena, California, United States of America*
[3] *Department of Aeronautics, Imperial College London, London, United Kingdom*
[4] *Department of Aeronautics & Astronautics Engineering, Tsinghua University, Beijing, China*

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Many innovative approaches to solar sail mission and trajectory design have been proposed over the years, but very few ever have the opportunity to be validated on orbit with real spacecraft. Thin-Film Spacecraft/Lander/Rovers (TF-SLRs) are a new class of very low cost, low mass space vehicle which are ideal for inexpensively and quickly testing in flight new approaches to solar sailing. This paper describes using TF-SLR based micro solar sails to implement a generic solar sail test bed on orbit. TF-SLRs are high area-to-mass ratio (A/m) spacecraft developed for very low cost consumer and scientific deep space missions. Typically based on a 5 µm or thinner metalised substrate, they include an integrated avionics and payload system-on-chip (SoC) die bonded to the substrate with passive components and solar cells printed or deposited by Metal Organic Chemical Vapour Deposition (MOCVD). The avionics include UHF/S-band transceivers, processors, storage, sensors and attitude control provided by integrated magnetorquers and reflectivity control devices. Resulting spacecraft have a typical thickness of less than 50 µm, are 80 mm in diameter, and have a mass of less than 100 mg resulting in sail loads of less than 20 g/m^2. TF-SLRs are currently designed for direct dispensing in swarms from free flying 0.5U Interplanetary CubeSats or dispensers attached to launch vehicles. Larger 160 mm, 320 mm and 640 mm diameter TF-SLRs utilizing a CubeSat compatible TWIST deployment mechanism that maintains the high A/m ratio are also under development. We are developing a mission to demonstrate the utility of these devices as a test bed for experimenting with a variety of mission designs and control laws. Batches of up to one hundred TF-SLRs will be released on earth escape trajectories, with each batch executing a heterogeneous or homogenous mixture of control laws and experiments. Up to four releases at different points in orbit are currently envisaged with experiments currently being studied in MATLAB and GMAT including managing the rate of separation of individual spacecraft, station keeping and single deployment/substantially divergent trajectory development. It is also hoped to be able to demonstrate uploading new experiment designs while in orbit and to make this capability available to researchers around the world. A suitable earth escape mission is currently being sought and it is hoped the test bed could be on orbit in 2017/18.

Key Words: interplanetary CubeSat, micro solar sail, Spacecraft-on-Demand, thin-film spacecraft (TF-SLR), TWIST

1. Introduction

Solar sails have been of great interest as a potential tool for exploring the solar system and beyond, but only the IKAROS[1] mission has demonstrated solar sailing in interplanetary space to date. Missions such as LightSail-1[2] and NanoSail-D[3] have been flown in low earth orbit (LEO), but have mainly focused on demonstrating sail deployment mechanisms.

The cost and risk of flying technology demonstration missions for what many still consider an experimental approach is a significant barrier for the widespread adoption of this propulsion technique. With even low cost missions such as LightSail-1 reportedly having budgets in excess of one million US dollars, opportunities to try novel solar sail designs and control laws are few and far between, and are unlikely to be readily available to researchers in significant numbers.

A novel new class of very low cost low mass space vehicle the Thin-Film Spacecraft/Lander/Rover (TF-SLR) has been devised to address this issue. These devices are designed to be individually manufactured using specialized printing processes, initially on earth and eventually on orbit, using design rules provided in an electronic design kit to researchers who design their spacecraft and provide a single electronic file that specifies the manufacturing, deployment and operation of the device on orbit[4]. TF-SLRs are designed to be loaded by the hundred into low cost CubeSat standard compatible dispensers that can be launched to a suitable orbit by taking advantage of space agency and commercial LEO, geosynchronous and interplanetary rideshare opportunities. Sharing the cost of the CubeSat and its launch (typically between hundreds of thousands to low millions of US dollars) between hundreds of individual TF-SLRs dramatically reduces costs, greatly improving affordability and access to space for researchers and students.

A proof of concept mission is currently under development to launch a solar sail testbed to demonstrate the utility of this approach. At least one hundred TF-SLRs will be launched in an Interplanetary CubeSat Mothership (ICM) to demonstrate the deployment and operation of the ICM and TF-SLRs on orbit. An initial low altitude LEO deployment test to demonstrate the functionality of the ICM and TF-SLR dispenser mechanisms and the devices themselves will be followed by a solar sail testbed mission at an altitude sufficient to demonstrate solar sailing and the functionality of a variety of control laws. If successful, follow on missions are expected to combine further technology demonstrations with science missions.

2. System overview

The solar sail testbed consists of at least one hundred custom TF-SLRs loaded into a TF-SLR dispenser which has been integrated with an ICM bus to form a single 0.5U-3U CubeSat Design Specification [5] compatible spacecraft – the Solar Sail Testbed CubeSat (SSTC).

The SSTC is integrated with a suitable CubeSat deployer (for example, a P-POD or ISIPOD) qualified for the launcher provided by the rideshare provider, who command its deployment into space at a suitable point in their mission.

The SSTC and TF-SLRs are commanded and tracked by their operators using a combination of dedicated and shared UHF/VHF/S-band ground stations and radio telescopes around the world.

The mission is designed to be compatible with COSPAR planetary protection requirements [6] as well as national and international orbital debris mitigation regulations [7].

3. Thin-film Spacecraft/Lander/Rovers (TF-SLRs)

3.1. Overview

A TF-SLR is a self-contained spacecraft with attitude control, communications, compute, instruments, power management and other such attributes of a typical small spacecraft. Materials and devices are chosen such that the total mass of the final spacecraft is at mg to g scale with an area to mass ratio in the range 10-20 g/m^2 to optimize performance as a solar sail.

TF-SLRs are designed to be mass-custom manufactured, initially using low cost commercial off the shelf (COTS) multi-material printers and other tools on earth, and eventually by CubeSat scale spacecraft printers in space. These TF-SLRs consist of a thin-film substrate that have semiconductor dies, passive electronics, photovoltaic cells, reflection control devices, thermal control coatings, actuators, structure, conformal coatings and other elements printed, bonded or deposited upon them.

To be compatible with the current TF-SLR dispenser, a TF-SLR must present as an 80 mm diameter cylinder, 50 μm to 1000 μm thick with an at least 50 μm diameter wire hoop around at its circumference at one end. Individual devices must be capable of being one of a stack of heterogeneous devices in compression in the dispenser when stowed.

Once dispensed, TF-SLRs may maintain their shape as stowed, or reconfigure themselves. Proof of concept reconfigurable TF-SLRs that stow as 80 mm diameter cylinders and reconfigure themselves mechanically as up to 640 mm diameter membranes have been designed, as well those that inflate to form spheres and other shapes, or are designed using origami and kirigami techniques to unfold and achieve complex morphologies.

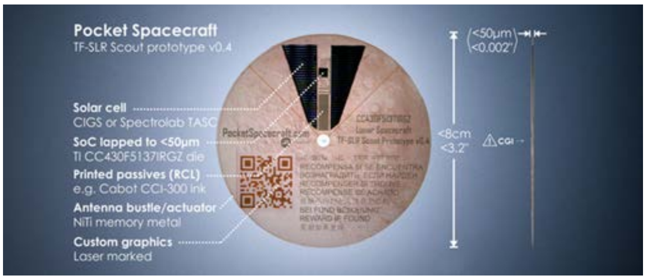

Fig. 1. A non-reconfiguring when dispensed proof of concept TF-SLR.

3.2. Substrate and structure

No specific substrate is mandated for a TF-SLR, other than it should satisfy the normal constraints for a material to be used in space with regards to outgassing and other such properties.

Typical solar sail materials such as CP1, Mylar and polyimide are all suitable for use as substrates. However, all designs to date have used bare or aluminized polyimide due to its low cost, ready availability in thicknesses ranging from 20 nm to 50 μm, and compatibility with the printing, bonding and deposition processes that have been explored.

The simplest TF-SLR format is an 80 mm disc, a format chosen to be compatible with the physical constraints of deployment from a CubeSat and to be compatible with tools and processes for manipulating 4 inch semiconductor wafers when mounted on a suitable jig.

Larger membrane designs that have been explored include those based on the TWIST origami inspired folding system which allows an up to 640 mm diameter membrane to be folded to be compliant with the 80 mm stowed constraint. Membrane gores have been designed that when bonded and filled with a sublimating power permit spherical and other shaped TF-SLRs to be dispensed. Other designs include pop up flaps, booms and other deployables, typically actuated by small quantities of memory metal or spring steel restrained by burn wires to implement instruments and attitude control devices such magnetorquers that can stow flat within the TF-SLR dispenser.

3.3. Power system

Initial TF-SLR designs are capable of being powered by a direct electrical connection during manufacturing and when stowed in their dispenser to permit testing and to receive firmware updates. During environmental testing and on orbit, current designs generate power from photovoltaics directly deposited onto the substrate by processes such as metal organic vapour deposition (MOCVD), or by bonding processed triple junction cells to the substrate or deposited metal with suitable epoxies. TF-SLRs requiring the integration of reflectivity control devices (RCDs) typically have them added at this stage.

Current designs directly power TF-SLR avionics from the photovoltaic devices to minimize complexity and cost. Potential power storage approaches utilizing (super)capacitors and thin film batteries have been investigated but have not yet proven necessary for initial applications where the priority has been keeping the devices as simple as possible and addressing discontinuities in power in software.

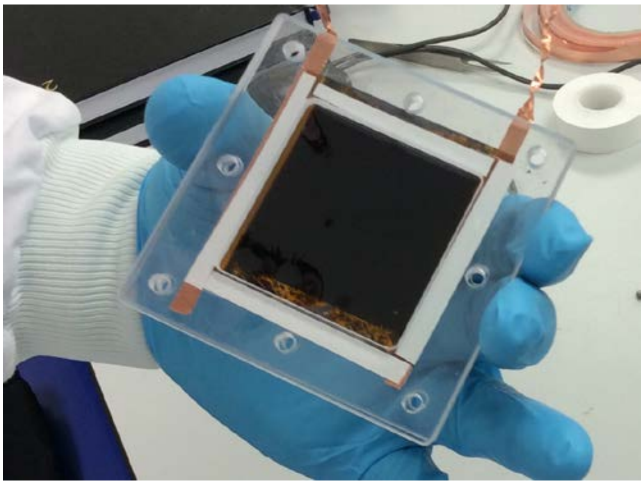

Fig. 2. TF-SLR polyimide substrate with CdTe photovoltaic in a jig.

3.4. Avionics and instruments

Once a TF-SLRs substrate and power system have been prepared, avionics and instruments are added. Currently a number of single die COTS System-on-Chip (SoC) architectures have been integrated into designs, for example, Texas Instruments CC430 family devices costing less than \$10 per die. A custom rad-hard bit serial based SoC is currently under development for implementation using a low cost shared wafer service targeting a per die price of less than \$100. These SoCs include an integrated processor (0.1-20 MHz), memory (0.1-4 KB), storage (0.1-64 KB), radio transceiver (0.01-10 W, UHF/VHF/S-Band, 0.1-1200 bps), input-output interfaces and timers.

A bare die is obtained directly from the foundry or by depackaging a surface mount device package. If suitable, the die is lapped from its standard thickness (typically 500 µm) to a minimum thickness (typically 50 µm or less) experimentally determined to be compatible with reliable operation after bonding directly to a TF-SLR substrate. The die is imaged with a digital microscope and compared with a previously obtained die map to confirm compatibility and orientation and bonded to an appropriate part of the substrate.

Any additional discrete dies or devices required for a specific TF-SLR design, for example to provide functions or instrumentation that cannot be included within the SoC such as accelerometers, crystals, imagers and similar are added in a similar manner.

The substrate is then imaged with sufficient fidelity (10 µm or better) to confirm the exact positions and orientations of all the elements bonded to the substrate such as dies, photovoltaics, reflectivity control devices, structures and their pads and contacts.

Antennas and impedance matching devices to support the communications subsystem are synthesized based on the frequencies that the TF-SLR is configured to support, with dipole, loop and patch antennas currently supported. Instruments to be printed are similarly synthesized with dust detectors, strain gauges and Langmuir probes chosen as initial proof of concept devices. Any mechanical reinforcement patterns such as rip stops, or actuator attachment points for elements such as burn or muscle wires, are integrated while maintaining appropriate keep clear areas where necessary.

The path and position of conductive tracks and any required passive support components such as capacitors and resistors are computed, taking into account any unexpected variations in positioning or orientation of devices during the manufacturing process.

Once the final layout of the TF-SLR has been synthesized, conductive, dielectric and resistive inks are printed using several passes of a multi-material printer, interleaved with passes through a cutting system to create cuts, fasteners such as buckles, and vias in the substrate. Initial TF-SLR designs are able to be manufactured by following an initial cutting pass with printing conductive, dielectric, resistive, and another conductive ink layer. The jig holding the substrate is turned over and the process repeated on the other side to complete the design.

3.5. Final processing and test

Any actuator or tie-down materials are added to TF-SLR, and a conformal coating is applied as the final deposition step if required. A probe card is connected to test points to power up and exercise all components of the TF-SLR. If successful, a bootloader is uploaded to the SoC to permit the TF-SLR firmware to be updated wirelessly at any point from manufacture to operation after dispensing in space. If the TF-SLR passes the initial test it is cut from its jig and transferred to a carrier case for storage and extended burn-in and environmental testing before integration in a TF-SLR dispenser.

4. Interplanetary CubeSat Mothership

4.1. Overview

A TF-SLR dispenser is required to dispense TF-SLRs in orbit. As the most cost effective way to access the largest range of orbits is currently the CubeSat format, and trajectories of greatest interest for solar sailing are in interplanetary space, the baseline carrier for TF-SLRs is an Interplanetary CubeSat Mothership (ICM).

This 0.5-3U radiation tolerant CubeSat is designed to be compatible with the widest range of launch vehicles and CubeSat deployers practical, is able to survive the cruise phase of an interplanetary rideshare mission without external power and with minimal thermal control, and is able to autonomously or on command dispense specific individual TF-SLRs at specific points in orbit once deployed. The ICM is designed to be as simple as possible while having at least two independent redundant approaches for providing its required functionality. The design is modular so that additional subsystems such as electric propulsion can added if required in future with minimal changes.

In addition to being a carrier and dispenser of TF-SLRs, the ICM is also designed to be able to act as a TF-SLR communications relay and navigation reference beacon, as well as hosting a limited number of non-dispensed TF-SLRs on its exterior.

4.2. Structure and dispenser

The ICM is built around the TF-SLR dispenser which uses a Pumpkin CubeSat Kit (CSK) large aperture cover plate compatible assembly with dual separation switches as its chassis. A 10-100 mm tall cylindrical stack of TF-SLRs, up to 1 mm of restraints, and a 10 mm thick dispenser/pusher mechanism including control electronics at the base of the stack, is positioned to pass through the aperture. Depending on the application, the stack of TF-SLRs can be configured to occupy the ‘tuna can’ volume of the CubeSat specification, be flush with the CubeSat deployer pusher plate face of the cover plate assembly CubeSat feet, or be flush with the exterior of the main cover plate. This flexibility allows other CubeSat systems such as deployable solar arrays to be stacked between the feet of the plate, or antennas to be wrapped around the CubeSat and cover plate as required.

The dispenser includes two independent mechanisms for dispensing TF-SLRs individually, with two independent sets of control electronics to initiate dispensing and report status. If either mechanism or set of control electronics fails, the other can be used. In the case of a jam or failure of both dispenser mechanisms, the option to initiate the ejection of the entire stack of TF-SLRs using a separate fall-back mechanism is available.

The dispenser is designed to be able to be dropped into existing validated third party CubeSat buses to allow missions to be built at minimal cost. The design maintains the standard functionality of the CSK cover plate such as separation springs, separation switches and compatibility with solar array clips. However, if building a complete custom ICM for deployment, standard elements are able to be replaced with elements with additional functionality, for example feet with integrated cameras for recording the dispensing of the TF-SLRs, mounting points for reaction wheels, or the integration of spot radiation shielding. If a fully custom ICM is required for a mission, then a complete parametrically specified CSK compatible structure can be synthesized and computer numerical control files and protocols to manufacture complete CubeSat specification compliant ICM structures 0.5-3U in size can be generated.

Once all the TF-SLRs have been dispensed, as the ICM uses redundant thin-film avionics bonded to the inside of the structure walls, the ICM is essentially a 100 mm square hollow aluminium tube. Hypervelocity impact experiments conducted with a light gas gun have demonstrated that the structure operates effectively as a Whipple shield, protecting thin film avionics on one side of the structure wall against micrometeoroid impacts on the structure material of the opposite wall.

4.3. Power system

The TF-SLR dispenser is designed to draw no more than 2.5 W for up to sixty seconds per dispensing action from a cold start with the vast majority of the power used to activate muscle wire actuators for individual TF-SLR dispensing, or burn wires for initialization of the system or the fallback ‘dispense all’ mode of operation.

If integrated with a third party CubeSat bus, the dispenser requires two independent 3.3 V @ 0.75 A supplies for maximum redundancy. If integrated with a dedicated ICM, the proof of concept avionics draw up to an additional 0.5 W during TF-SLR dispenser operation. The 2.5 W reserved for the dispenser is available when it is not in use to supply other subsystems such as communications.

To minimize complexity, all ICM systems are powered directly from solar arrays with no battery backup. The 0.5U reference ICM design uses two types of solar array, O88 thin-film TWIST arrays and backup 0.5U rigid deployable arrays.

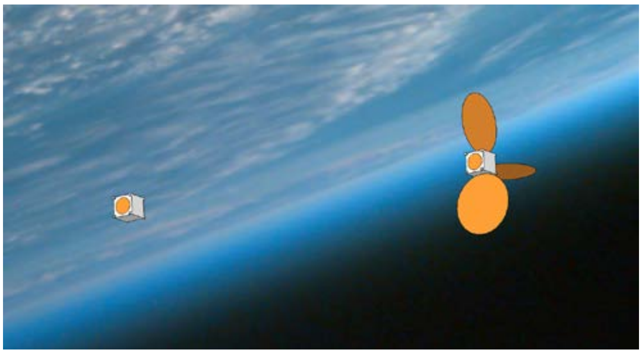

Fig. 3. Simplified ICM concept graphic showing TWIST array stowed (left) and deployed (right) from Z+ face, with TF-SLR dispenser on Z-.

The O88 thin-film TWIST arrays are 320 mm diameter TF-SLRs populated with at least 7 W end of life (EOL) of COTS triple junction cells, a magnetorquer coil, redundant avionics, and VHF, UHF and S-band antennas. The power and radio frequency connections are brought off the TWIST array by configuring part of the substrate as a flexible printed circuit board connection for the ICM bus. The TWIST arrays are mounted on a CSK solar array clip compatible printed circuit board and are deployed with redundant burn wires.

The 0.5U rigid deployable arrays are a CSK solar array clip mounted set of redundant burn wire deployed 0.5U FR4 rigid panels with COTS triple junction cells generating at least 7 W EOL per deployable array with integrated UHF and S-band antennas. Power and radio frequency connections are made via a flexible printed circuit board compatible connector.

4.4. Avionics and instruments

The ICM avionics package consists of an array of TF-SLRs configured to use external solar arrays instead of integrated photovoltaics.

Six independent TF-SLR devices with standard avionics are bonded to the inside walls of the ICM structure, one TF-SLR per wall. The substrates are shaped to match the interior wall dimensions and are extended to form flexible printed circuit board connections to the solar arrays and TF-SLR dispenser interfaces.

The six ICM TF-SLRs are configured as two groups (A and B) of three (0, 1, and 2), with each group having one TF-SLR able to support VHF, UHF and S-band communications each. The ICM TF-SLRs are positioned in pairs on opposing faces, for example, ICM TF-SLR$_{A0}$ and ICM TF-SLR$_{B0}$ are positioned on the X+ and X- interior walls.

Each ICM TF-SLR can communicate with each other and the TF-SLR dispenser using redundant communications links and cooperatively manage the operation of the ICM and the dispensing of TF-SLRs.

5. Mission concepts

5.1. Overview

The goal of the solar sail testbed is to provide as many opportunities as possible for researchers and students to try novel solar sail control laws and concepts safely in space. All elements of the system are being placed in the public domain to allow researchers from as many countries as possible to participate while minimizing the impact of export control laws.

The communications systems have been designed to be compatible with both ITU amateur satellite 8) and CCSDS 9) requirements for maximum flexibility. Suitable ground segments to support communications and navigation have been implemented and tested and are based on systems that can be found at low cost in the amateur radio community or by using existing radio astronomy infrastructure.

The goal is to test the system in two phases – an initial LEO test of the core TF-SLR hardware, dispenser and ICM, followed by an earth escape demonstration of solar sailing. If successful, it is hoped that that these missions will be followed by a regular series of missions combining technology demonstrations of new solar sailing approaches and science missions enabled by these technologies.

5.2. Low earth orbit (LEO) mission

The initial solar sail testbed mission will be to a sub International Space Station (ISS) orbit to verify the operation of the TF-SLR and ICM hardware on orbit. It is anticipated that the mission will last for less than thirty days with the deployment of at least one 0.5U ICM containing at least one hundred TF-SLRs from a suitable launch vehicle or the ISS.

An ICM will initialize itself after the standard deployment delay from its CubeSat deployer, and will demonstrate its successful operation in safe mode for a period of at least forty eight hours, including demonstrating low power beaconing and responding to the safe mode commands from main ground stations in China, the United Kingdom and the United States of America, and backup ground stations elsewhere. Once safe mode checkout is complete, the ICM will deploy its solar arrays and collect and beacon status data for at least another twenty four hours. The ICM will continue to operate in this mode while orbit determination experiments are run at the ground stations until one week before the ICM is predicted to reenter the atmosphere. The ICM will then be commanded to dispense a predetermined sequence of TF-SLRs. After being dispensed, TF-SLRs will execute predetermined mission plans including beaconing data, demonstrating pre- and post-dispensing firmware upgrades, direct and relayed communications via the ICM, and orbit determination experiments.

5.3. Earth escape (EE) mission

Once the operation of TF-SLRs, TF-SLR dispenser, and ICM have been validated in LEO, an earth escape solar sailing mission will be performed. A number of ride share opportunities for deploying a 1U CubeSat in a suitable starting orbit for TF-SLRs to achieve earth escape have been identified including insertion into geosynchronous graveyard disposal, trans-lunar injection and lunar orbits.

A duplicate of the LEO mission hardware will be flown on the spacecraft or launch vehicle providing the rideshare to the target orbit for TF-SLR dispensing. The ICM will be deployed from a suitable CubeSat deployer, and ICM safe mode checkout, solar array deployment and orbit determination experiments will be performed as in the LEO mission. The same communication and navigation systems validated during the LEO mission will be used for the twelve month EE mission.

Once the health and position of the ICM has been confirmed, a small (<10) initial test dispensing of TF-SLRs will be performed. These TF-SLRs will also go through on-orbit checkout procedures similar to the ICM immediately after dispensing including accurately determining their orbits.

When the checkout phase has been completed, the TF-SLRs will execute algorithms to demonstrate their ability to raise their orbits slightly (<100 km) in a controlled manner. Once their performance has been validated, they will start to execute predetermined experiments to demonstrate formation flying and orbit changing manoeuvres.

The most challenging of these would be achieving escape from the geosynchronous graveyard disposal launch opportunity. Modelling deployment of a 1U ICM in such an orbit which deploys TF-SLRs with appropriate RCDs, suggests that TF-SLRs could safely achieve earth escape within eight months of being dispensed.

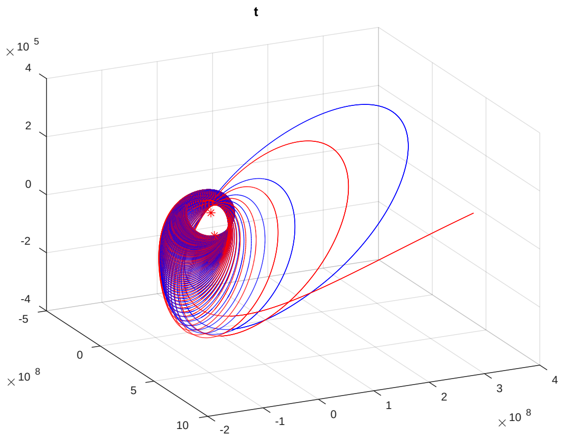

Fig. 4. Output of MATLAB model showing a pair of TF-SLRs (red and blue) achieving earth escape from a geosynchronous graveyard disposal orbit using different control laws (axis units: km).

Once the initial checkout batch of TF-SLRs has successfully commenced their missions, the rest will be available to be dispensed over a period of up to one year. It is anticipated these follow on missions will mostly be defined by uploading the necessary flight software to the TF-SLRs via the ICM after launch for maximum flexibility.

As the ICM and TF-SLRs reach the end of their operational life they will be passivated and deactivated automatically or on command as appropriate.

6. Conclusion

We believe that the solar sail testbed could be an important tool both for technology demonstration and for space science researchers. We are interested in making it accessible to the widest possible community and invite those who wish to use the testbed to contact us to discuss opportunities to participate in these missions.

The current mission concept assumes that TF-SLRs will be manufactured on earth for launch and dispensing in orbit, with manufacturing TF-SLRs in space the eventual goal. With the ability to upload control laws to TF-SLRs before and after dispensing, we hope that the potential ability to take new solar sailing concepts from idea to deployment in just a few hours will provide an exciting new capability for the community.

Acknowledgments

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