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Design and Overview of the Solar Cruiser Mission

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ABSTRACT

Solar Cruiser is a Small Satellite Technology Demonstration Mission (TDM) of Opportunity to mature solar sail propulsion technology to enable near-term, high-priority breakthrough science missions as defined in the Solar and Space Physics Decadal Survey. Solar Cruiser will demonstrate a “sailcraft” platform with pointing control and attitude stability comparable to traditional platforms, upon which a new class of Heliophysics missions may fly instruments. It will show sailcraft operation (acceleration, navigation, station keeping, inclination change) immediately applicable to near-term missions, and show scalability of sail technologies such as the boom, membrane, deployer, reflectivity control devices for roll momentum management to enable more demanding missions, such as high inclination solar imaging.

A team led by the NASA Marshall Space Flight Center is developing the Solar Cruiser with partners Ball Aerospace and Roccor (a Redwire company). Ball is responsible for procuring a Venus class microsat commercial bus from Blue Canyon Technologies, defining all necessary mission-specific modifications, and performing the Integration and Test of the Bus with the Solar Sail System to form the completed sailcraft. Ball will also procure the IRIS radio from Space Dynamics Laboratories and develop the adapter and harnessing that interfaces to the Launch Vehicle. Roccor will integrate the Solar Sail System (SSS), including the sail membrane from their Subcontractor NeXolve, the Triangular, Rollable and Collapsible (TRAC™) Boom, the LISAs (Lightweight Integrated Solar Arrays) and momentum management Reflective Control Devices (RCDs), before providing it to Ball for Integration and Test. Roccor will also build the Active Mass Translator (AMT), which moves the Sail relative to the Bus to control momentum in the pitch/yaw directions, while the RCDs provide roll control. MSFC manages the overall mission and provide the specialized solar sail attitude determination and control system (SSADCS) algorithms and software necessary to fly the sailcraft. The SSADCS software created for this mission will autonomously operate the AMT and RCDs to provide complete momentum control of the sailcraft. Bus-mounted Electric Propulsion thrusters are included to provide auxiliary momentum management, if required.

Solar Cruiser will launch as a secondary payload with NASA’s Interstellar Mapping and Acceleration Probe (IMAP) in early 2025. The sailcraft will separate from the launch vehicle on a near-L1 trajectory (Sun-Earth Lagrangian Point 1; sunward of L1 along the Sun-Earth Line) and complete its primary mission in 11 months or less. During this time, Solar Cruiser will complete and fully characterize a large solar sail deployment (1,653 square meters/17,793 square feet), sail operation, station keeping in a sub-L1 halo orbit, inclination changes, and a roll demonstration.

This paper provides a mission and sailcraft design overview, including objectives and planned operations of the technology demonstration mission. It presents the latest findings from technology maturation efforts, major program design reviews, and initial launch integration planning.

INTRODUCTION

Using reflected sunlight to obtain thrust, solar sails can propel small spacecraft through space without fuel, making them useful for reaching destinations that require large ΔV. Solar Cruiser demonstrates a solar sail-propelled, stable imaging and science instrument platform to serve as a pathfinder for missions to observe the solar, heliosphere, and geospace environments from unique, propulsion intense, vantage points. Examples of these vantage points include sustained observations away from the Sun-Earth line (SEL); sustained sub-L1 (sunward of L1 along the SEL) station keeping for improving space-weather monitoring, prediction, and science, and supporting human spaceflight crew safety and health needs; sustained in-situ Earth magnetotail measurements; those that require a high inclination solar orbit; and Earth polar-sitting and polar-viewing observatories.

MISSION GOALS

The overarching goal of Solar Cruiser is to demonstrate solar sail propulsion technology to enable near- and mid-term Heliophysics science missions up to and including high solar inclination orbits, sub-L1 halo orbits, non-Keplerian solar and other planetary body orbits. This is achieved through demonstration of the below four specific objectives.

Objective 1: Show sailcraft operation (acceleration, navigation, station keeping) immediately usable and applicable for near-term mission needs. For example, by placing space weather instruments on a Solar Cruiser class sailcraft and stationkeeping along the SEL sub-L1, solar wind observations could result in >50% increase in warning times for impending coronal mass ejections and other solar wind disturbances relative to observations at L1 (Figure 1). Such solar wind disturbances drive geomagnetic storms that pose a threat to the integrity of the power grids and other terrestrial infrastructure. NOAA has defined an objective of making solar wind observations at up to twice the distance from Earth along the SEL as L1 (i.e., up to a 100% increase in warning times).[1]

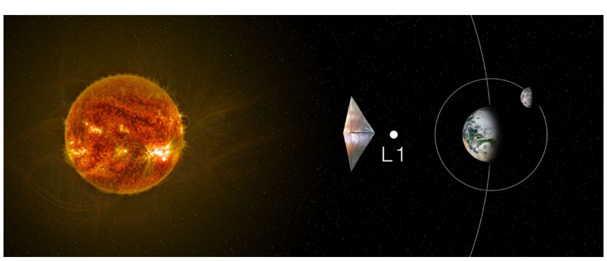

Figure 1. By placing a sailcraft sunward of L1 along the SEL, warning of impending solar storms could be increased by 50% or more.

Objective 2: Show scalability of sail technologies (boom, membrane, deployer, Active Mass Translator (AMT) for pitch/yaw momentum management, reflective control devices (RCDs) for roll momentum management) and design to enable more demanding missions, such as high inclination solar imaging. Obtaining sustained observations of the sun at high inclination is extremely propulsion intense and can be accomplished by a sailcraft, properly instrumented, navigating to 0.48 AU and canting the solar sail to maximize out of plane thrust, slowly changing the sailcraft's Heliospheric inclination until the desired solar latitude is reached. The process is illustrated in Figure 2.

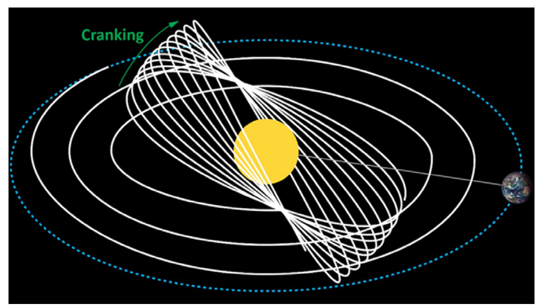

Figure 2 A sailcraft can slowly change its heliocentric inclination without the use of propellant.

Objective 3: Demonstrate that sailcraft pointing control and attitude stability is comparable to that achievable with traditional platforms to validate sailcraft usability with science instruments. The pointing accuracy is set to be compatible with a range of possible Heliophysics science instruments. Stability and jitter requirements are set by exposure time and spatial resolution. The jitter is set by envisioning a Doppler magnetograph to have a requirement of ~0.1–0.25 arcsec/sec (3-sigma). Typical Doppler magnetographs utilize internal tip-tilt image stabilization mechanisms (e.g., Solanki et al. 2019) to achieve a 10–20x reduction in jitter for pitch and yaw.

Objective 4: Demonstrate sail-embedded photovoltaic power generation technology to support future sailcraft systems and science instrument power needs for long-lived missions. The pointing accuracy is set to be compatible with a range of possible Heliophysics science instruments. Stability and jitter requirements are set by exposure time and spatial resolution. The jitter is set by envisioning a Doppler magnetograph to have a requirement of ~0.1–0.25 arcsec/sec (3-sigma). Typical Doppler magnetographs utilize internal tip-tilt image stabilization mechanisms (e.g., Solanki et al.

2019) to achieve a 10–20x reduction in jitter for pitch and yaw.

SAILCRAFT OVERVIEW

The sailcraft is composed of the Integrated Sailcraft Bus (SB) and Solar Sail Propulsion Element (SSPE). Figure 3 is the expanded view of Solar Cruiser with major systems identified. The X-SAT Venus-class microsat bus from Blue Canyon Technologies (BCT) will be augmented with a deep space Iris transponder from Space Dynamics Laboratory (SDL). The SSPE consists of a 2-axis translating mechanism (Active Mass Translator (AMT)), Solar Sail System (SSS), and Solar Sail Attitude Determination and Control System (SSADCS) software.

The deployed solar sail, supported by high strain composite booms, measures 42 m by 42 m. Momentum management, executed through the SSADCS software and crucially important for successful mission execution, is accomplished through operation of the AMT, embedded sail technologies, and off-the-shelf bus ADCS components. The AMT adjusts the sailcraft center of mass relative to the solar sail center of pressure, offsetting pitch/yaw disturbance torques. The solar sail embedded Reflective Control Devices (RCDs) address disturbance torques about the axis normal to the solar sail (roll) by changing their optical properties with applied voltage.

Solar sail embedded photovoltaics, the Lightweight Integrated Solar Array (LISA), will demonstrate power generation capability for technologies where bus-supplied power may be infeasible (e.g., outboard RCDs for larger solar sail systems).

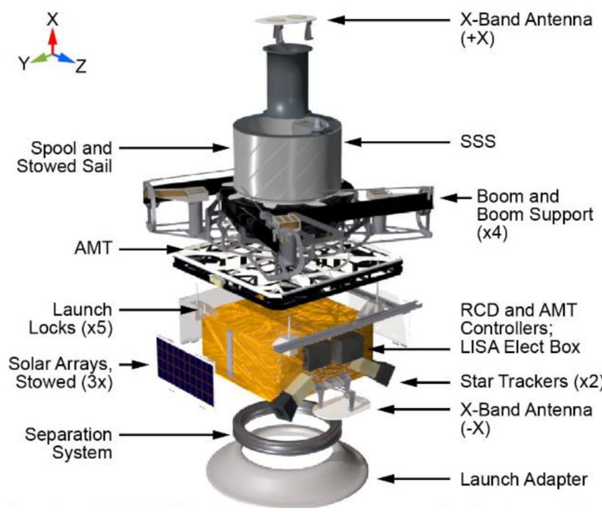

Figure 3: Expanded View of the Solar Cruiser Sailcraft

Integrated Sailcraft Bus

To leverage heritage and maintain cost efficiencies, the Integrated Sailcraft bus has been designed around a the BCT X-SAT Venus class commercial microsat bus. Many of the subsystems of this product are planned for use in a standard configuration, with only minor modifications utilized for the Solar Cruiser mission.

The bus structure is required to provide an interface for the SSPE and housing for the bus internal components. It is also required to withstand the predicted launch and operational loads. The primary structure resembles a box in shape and encloses the command and data handling (C&DH), telecom, and ADCS software subsystems. While the “top” face of the box is customized for SSPE mechanical interface needs, the other panels, internal bracketry, and secondary structure components are left unchanged from the standard product bus.

The telecommunications (telecom) subsystem provides engineering and mission data downlink and command uplink capabilities, while supporting navigation. Hardware consists of an SDL Iris radio, couplers, filters, cables, and antennas. The X-band Iris radio was flight qualified on the MarCO mission, is DSN-compatible, and fits in a microsat bus volume.[2] The telecom subsystem has multiple downlink rates based on mission range and pointing error from off-boresight orientation of the low gain antennae.

Power is supplied by a three-wing non-articulating deployable solar array that provides sufficient power capability, including at end of life. The arrays used are standard Cubesat BCT products, which feature a better mechanical footprint aligned with the Solar Sail while still providing the needed power.

The bus attitude determination and control system (ADCS) is single string with two star trackers and four coarse Sun sensors to provide primary attitude knowledge and control. Stellar-based attitude estimates are computed autonomously on board, with no ground processing required. A micro electro-mechanical systems (MEMS) inertial measurement unit (IMU) within the avionics is used during safe and cruise modes to improve sailcraft stability if star tracker attitude solutions are not available. Four finely-balanced reaction wheels are mounted to interior bus structure perform fine attitude control.

In addition to the solar sail, Solar Cruiser also features an in-bus propulsion system. For dumping reaction wheel (RW) momentum prior to sail deployment, four indium field-emission electric propulsion (FEEP) multi-emitter NANO Thrusters are used. Each thruster is mounted at an angle on the interior of the bus within the separation ring. Propulsion and propellant analysis has large margins, and shows that this propulsion system can provide a backup control capability for the RCDs and supplementary capability to the AMT after the sail is deployed, if required.

All SSPE electrical interfaces, data flow and storage are accommodated in the bus command and data handling system. Hardware for this is centered around an integrated flight avionics unit, which features a dua core ARM processor, flash memory, appropriate interface channels, and field programmable gate array (FPGA) code. In addition to interfacing and data flow, the C&DH system also houses the bus flight software (FSW) for use prior to solar sail deployment, and the mission custom Solar Sail Attitude Determination and Control System (SSADCS) Software as a digitally hosted payload. The FSW architecture is identical to every Blue Canyon microsat and shares the core software with all Blue Canyon avionics modules and CubeSats, which have successfully flown. This standard bus FSW meets the needs of Solar Cruiser with only minor changes needed to the existing payload interfaces, resulting in an estimated 95% bus FSW reuse.

In a similar manner, the thermal control system uses the same methods that have been successfully used on *Kepler*, *Deep Impact*, and *NEAS*. These include the use of multilayer insulation (MLI), material surface finishes, radiators, conductive and isolating interfaces, and heaters. The Solar Cruiser thermal model is fully integrated, including the bus and all SSPE components listed below.

Solar Sail System (SSS)

The Solar Sail System (SSS) provides the large, propulsive surface required for thrust generation. The SSS is based on a proven four-quadrant sail design. The four triangular sail quadrants are folded and co-spooled onto a central hub, and are then deployed out and tensioned by four 30m long High Strain Composite (HSC) Triangular Rollable and Collapsible (TRAC) booms. The four booms are also co-spooled onto a central hub and deploy concurrently using a single motor-driven mechanism, resulting in a mass and volume minimized system. The Carbon Fiber Reinforced Polymer (CFRP) construction of the booms offers low mass, high stiffness, and near-zero Coefficient of Thermal Expansion (CTE), resulting in a highly stable deployed system.

Embedded into the large 2.5-micron thick sail membrane are two key technologies that will be demonstrated as part of Solar Cruiser: 1) Reflectivity Control Devices (RCDs), and 2) the Lightweight Integrated Solar Array (LISA). The RCDs change reflectivity from diffuse to specular with the application of a voltage, thus generating a torque for Sailcraft roll control. The LISA experiment will show the feasibility of utilizing sail-embedded photovoltaics to generate the necessary power for RCDs or other devices upon the Sailcraft.

Active Mass Translator (AMT)

The Active Mass Translator (AMT) is a two-axis translation table designed to shift the Sailcraft's Center of Mass with respect to the deployed sail's Center of Pressure, thereby providing torques necessary to manage the Sailcraft's momentum in the pitch and yaw axes. This simple, low mass device comprises of linear rails and carriages allowing translation to a precise position, as commanded by the SSADCS software, using motor-driven lead screws.

Solar Sail Attitude Determination & Control Software

The SSADCS software is the "brains' of the sailcraft system and works in both continuous (momentum control) and discrete (maneuver command) modes. In the autonomous mode, the software takes inputs from the sailcraft sensor suite and performs on-board processing. SSADCS software will enable demonstration of slewing and pointing performance capabilities in-line with science needs for a future operational mission.

The SSADCS software development heavily leverages the similar development effort for the *NEAS* SSADCS [Heaton 2017, Orphee 2017] with changes accounting for the Solar Cruiser-specific actuators (notably RCDs). The SSADCS software model and associated algorithms are developed at MSFC and delivered to Ball for integration with the bus FSW.

Context Camera

A Context Camera, whose configuration and functionality are currently being defined, will image at least one of the sail quadrants. The images will be used to evaluate the sail's deployment state, provide insight into the nature of the tensioned state of the sail against predictions, evaluate the sail integrity (due to possible tears or micrometeoroid impacts), and evaluate the in- and out-of-plane sail deflection. Based on the observed wrinkles, curvature, and the amount of light detected by the camera sensors, a model will be developed that maps the images to shape and stress distribution. The model will be used to infer the optical pressure on the sail, the torque it exerts due to the non-uniform sail shape, and the sail acceleration.

PLANNED OPERATIONS

As a rideshare payload on the IMAP mission, Solar Cruiser is do-no-harm to the primary payload and powered off at launch. Upon separation from the launch vehicle, the sailcraft will execute stored commands and autonomously detumble, sun-point, and deploy solar arrays. Contact will be then established with the NASA Deep Space Network (DSN) and commanded from the NASA MSFC Huntsville Operations Support Center (HOSC).

Over the subsequent weeks, the sailcraft will be commissioned in the solar-sail stowed state, releasing internal launch locks, checking systems functionality (e.g., via AMT actuation and acquisition of Context Camera imagery), and establishing thermal non-operational and operational limits. The sailcraft will perform a passive, ballistic transfer until the solar sail deployment conditions are satisfied. During this period, attitude determination and control will switch from the off-the-shelf capabilities of the bus to SSADCS software.

The solar sail deployment will commence via ground command with motor activation, boom extension, release of sail restraint, and unfurling of the four solar sail quadrants. High priority imagery will be downlinked to help validate a successful deployment. Characterization of the deployed solar sail will be performed by adjusting the sailcraft attitude and measuring imparted disturbance torques. The SSADCS software will autonomous command the AMT, RCDs, and Reaction Wheels (RWs) to manage momentum and follow an established pointing schedule. As the control actuator, the RWs will be monitored by the SSADCS and desaturated with the SSPE technologies.

The thrusting performance will be evaluating in the transfer to a Halo orbit sunward of Earth-Sun L1. Once the sailcraft reaches the insertion point, it will maintain that orbit demonstrate long term stability and extensibility to future missions.

Following the Halo orbit demonstration, the sailcraft will demonstrate the capability to perform heliocentric inclination change by adjusting attitude and thrust application out of the ecliptic plan of the solar system. The roll control actuator will be switched from Reaction Wheels to RCDs to demonstrate extensibility of the technology to much larger solar sails.

Fault detection and response capabilities throughout the mission will leverage the off-the-shelf bus capabilities but also need to be augmented to account for unique aspects of a solar sail mission. Given the continuous thrust, application of disturbance torques, and infrequent contacts with DSN, on-board autonomy will ensure the sailcraft responds in a manner that balances the technical resource needs of the sailcraft (e.g., power), management of disturbance torques, and minimize misapplication of thrust that could put satisfying mission objectives at-risk.

DESIGN STATUS

Throughout the proposal process and initial program work in Phase A, the Solar Cruiser team has laid a solid design foundation for the program. Work has already begun in many important areas, and several design reviews and milestones have already been achieved.

Technology Maturation Efforts

Solar Cruiser developed a detailed Technology Maturation Plans (TMP) for each of the sail technology systems. This SSS Technology Maturation Plan (TMP) was developed using the Technology Assessment Process (TAP) provided in the Stand Alone Missions of Opportunity Notice (SALMON) library which is taken from the NASA Systems Engineering Handbook (SP-2016-6105-Rev2). The TAP requires a baseline technology maturity assessment for TRL followed by an assessment of Advancement Degree of Difficulty (AD^2) prior to finalization of the TMP. The SSS, AMT, and SSADCS will be advanced to TRL 5 on the component level then collectively on the system level prior to the Project's Preliminary Design Review (PDR). The system will be advanced beyond TRL 5 prior to the Critical Design Review (CDR) to reduce risk to the extent possible on the ground prior to flight.

The advancement plans revolve around a milestone-driven schedule developed that includes non-advocate reviews to assess progress and plans at key development points. The first of these, a Technical Concept Review (TCR) was held February 25–26, 2020.

Major Program Design Reviews

During Phase A, a Concept Study Report and Proposal was produced and delivered on July 2, 2020. A "Site Visit" was held remotely (due to the COVID-19 Pandemic) in September, with Roccor and Ball participating from Ball's location in Boulder, CO; and MSFC participating from Huntsville, AL. Ball and Roccor were put on contract early in 2021 and began work on requirements leading up to a successful System Requirements Review, held virtually on April 20 and 21.

The program will hold several internal tabletop and technology maturation reviews in the late-summer and early-fall of 2021. These will culminate in a program Preliminary Design Review, currently planned for November 2021. Once approved, the program will progress into Phase C and continue with additional reviews into 2022 and beyond.

Initial Launch Integration Planning

In late 2020, Solar Cruiser was officially manifested as a Rideshare Payload on the NASA IMAP Mission. Prior to this selection, initial requirements surrounding Launch Integration, used to drive initial spacecraft design concepts, were outlined in the "NASA's Mission Specific Evolved Expendable Launch Vehicle Secondary Payload Adapter System Interface Specifications For Heliophysics Missions of Opportunity" document.[3] Solar Cruiser was initially allocated a ESPA Grande sized volume, with a system "not-to-exceed" mass requirement of less than 320 kg. Due to the mass-sensitive nature of the solar sail demonstration on Solar Cruiser, initial design concepts were already well within these mass and volume limits. Other environmental, interface, and ground processing information in this document drove the preliminary design of the Solar Cruiser sailcraft. The program's response to these requirements were documented in a Launch Service Interface Requirements Document, which was included in program proposal and Phase A material.

By the time Solar Cruiser received the official manifesting award notice, the SpaceX Falcon 9 Launch vehicle had already been selected as IMAP's ride to space.[4] Shortly after this selection, the team began interfacing with NASA Launch Services Program and SpaceX personnel to begin initial Launch Integration planning discussions and to determine how the initial launch interfacing requirements would change with the selection of Falcon 9 as the Launch vehicle. Initial Launch planning, Coupled Loads Analyses, and other integration work are underway, and will continue throughout the program development schedule. The culmination of all these efforts support a current target launch date in Q1 2025.

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