Solar Physics Observer and Transmitter

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The Request for Proposal (RFP) given by the AIAA specifies that the mission designed will launch one or more exploration assets to space to meet three requirements: to meet the National Academies of Science's Heliophysics priority investigations as outlined in the 2024 Decadal Survey for Solar and Space Physics (provides new useful Heliophysics and space weather data for more scientific research and improved understanding, as well as adding to existing observatories and missions for long-term sustainability, use this data to create predictive models grounded in physics, and seeing if this new understanding applies beyond our solar system); to meet NASA's Moon to Mars Objectives (relevant to this mission are SPOT's ability to assist Earth-independent navigation systems for deep space and its ability to monitor and forecast radiation that may predict all-clear periods) and to provide communication capability for potential crewed missions in Earth orbit and to Mars on a $400 million budget for at least 15 years. We propose that the Solar Physics Observer and Transmitter (SPOT) be built twice and plan to be launched by a SpaceX Falcon 9 in separate flights, launching them in 2031 and 2032. They will then be injected into L4 and L5 in the Sun-Venus planetary system. To satisfy the primary objective of maintaining near-continuous communication to Earth and Mars, a dual-satellite communication architecture is proposed. This requires two spacecrafts as a redundancy factor mitigating the

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communication blackouts that each spacecraft will experience, allowing for constant communication uptime without significant degradation or loss of signals. Once both SPOTs have reached their destinations, they will begin observing solar phenomena, noting locations and activity of sunspots, solar flares, prominences, and coronal mass ejections (CMEs). This new data, along with previous data from similar missions, will be used via machine learning to develop a predictive algorithm to forecast the formation of solar weather. This is intended for the more dangerous phenomena, including solar flares and CMEs, but predicting sunspots would be a significant milestone for Heliophysics. More importantly, the satellites will be able to observe changes in the Sun's magnetic field and solar wind and be exposed to space weather phenomena that threaten any space missions from Earth to Mars. If any weather is bound to affect that region of space of and between the two bodies, the satellites will send out warning signals using NASA's Deep Space Network to alert relevant authorities regarding the additional risk to mission performance.

I. Introduction

A. Background/Relevance
The sun is the solar system's main light and solar weather source, providing much needed information about physics over hundreds of years as humanity's understanding and equipment has increased. As humans seek to venture beyond Earth, protecting astronauts and equipment in space and on Earth are top priorities, and it is imperative that humanity develops longer prediction forecasts to accomplish this.

B. Project and Team Objectives
The Request for Proposal (RFP) given by the AIAA specifies that the mission designed will launch one or more exploration assets to space to meet three requirements: to meet the National Academies of Science's Heliophysics priority investigations as outlined in the 2024 Decadal Survey for Solar and Space physics, to meet NASA's Moon to Mars Objectives, and to provide communication capability for potential crewed missions to Mars on a $400 million budget for at least 15 years [3, 8].

C. Mission Scope
The Solar Physics Observer and Transmitter (SPOT) will be launched by a SpaceX Falcon 9 in December 2027. Engineers will monitor the satellites and adjust accordingly to better react to space phenomena. The satellites en route to L4 and L5 in the Sun-Venus planetary system will maintain constant communication with Earth. They will reach orbit in four or five months. There, the satellite will begin observing phenomena from the Sun. Data will include noting locations and activity of sunspots, solar flares, prominences, and coronal mass ejections (CMEs) and other supplementary data. This new data, along with previous data from similar missions, will be used via machine learning to develop a predictive algorithm to forecast the formation of solar weather. This is intended for the more dangerous phenomena, including solar flares and CMEs, but predicting sunspots would be a significant milestone for Heliophysics.

II. Mission Concept and Operations

D. Concept of Operations
SPOT will commence manufacturing in January 2026. From there, it will enter assembly in January 2027 and conduct material testing in November the same year. Ground crews, manufacturers, and engineers will conduct a series of environmental and stress tests to ensure the integrity and functionality of SPOT. After sufficient testing, SPOT will prepare for two launches: one in June 2031 and the other in June 2032. Following launch, the spacecraft will begin its trajectory towards satellite separation in June 2034; and reach the L4 and L5 Lagrange points by November 2034.

Once SPOT reaches its orbit, it will begin collecting data and training the onboard and Earth ML with its variety of onboard instruments with new data. Both satellites will maintain communications with Earth, Mars, and send signals and reports of solar weather activity such as coronal mass ejections, solar energetic particles, and solar flares.

A budget has been prepared regarding the ground crew of the Solar Physics Observer and Transmitter (SPOT) will be paid according to the GS Salary Table 2026, grades 8 through 12 depending on the employee [2]. The average estimate for an eight-person team working for three years from CDR to Launch will require $2,073,600 in salaries. For the entire 15-year mission lifetime, the ground crew will be paid $8,985,600 neglecting budget cuts, administrative shutdowns, and overtime. A total of $12,192,768 will be allocated from the $400 million budget to support these professionals.

Figure 1: Concept of Operations infographic showing the three phases of the mission: Launch, Arriving at L4 and L5 Destinations and Deploying Instruments, and then Starting Data Collection.

III. Mission Architecture

E. Orbital Mechanics

The designated mission orbit will be a Lissajous orbit about the L4 and L5 libration points in the Sun-Venus planetary system. These points are chosen because they exhibit adequate line-of-sight conditions where at least one spacecraft is accessible for a ground station on Earth and that they are relatively simple to solve towards. Furthermore, these orbits allow efficiency in the spacecraft design where the delta-v budget is allowed to be small. The stability of L4 and L5 points are such that once the spacecraft has reached the target orbit, the estimated annual cost of station keeping is less than 1 m/s. To find the optimal launch windows, date-spans are provided for launch and arrival dates, where Lambert's problem is solved for all pairs of dates. This constructs a porkchop plot that shows the optimal launch window to minimize ΔV, whereas the optimal launch windows have been found by R. C. Rangel [23]. As work progresses, an investigation into a more complex trajectory to deposit both satellites in one flight will be made, but this simpler approach is currently being considered so we may expect to launch the first SPOT satellite towards the L5 point in May 2031 and the second SPOT satellite in December 2032. All satellites should be deposited properly by June 2033.

Once both SPOTs have been deposited into the L4 and L5 points, the steady-state solution is not critically important to be modeled [24]. It is expected that the stability of these Lagrange points will allow the satellite to be "captured" into these positions [24]. The autonomous capability of the SPOT to orient itself will compensate primarily for solar radiation pressure as the most dominating perturbing force upon the spacecraft.

IV. Satellites

F. Propulsion and Attitude Control

Propulsion system options for satellites are limited due to the projected lifespan of the spacecraft. A required long lifespan of the spacecraft demands a high specific impulse from the propulsion system. The station-keeping maneuvers used to maintain the satellite in proper orientation and position require the thrust output to be vectored and throttleable. These requirements thus narrow down the potential choices to two main systems: electric ion thrusters or liquid bipropellant engines. Both systems do satisfy the requirements, but electric ion thrusters outperform liquid bipropellant engines in these metrics, as electric ion thrusters can operate at levels of specific impulse far surpassing liquid engines. Additionally, the ease of distributing electric power makes the thrust highly adjustable, allowing the spacecraft to make simpler maneuvers.

Thermal protection considerations, solar weather phenomena, and communications require orientation control. The attitude control system must be reliable, robust, and accurate. Three types were considered: hot gas propulsion, cold gas propulsion, or reaction wheels. Hot and cold gas propulsion is simpler because the system generates thrust by accurate expulsion of pressurized gases. However, reaction wheels express finer minute control. Reaction wheels have a higher lifespan over hot and cold gas propulsion since they do not rely on a finite reservoir of fuel. Therefore, reaction wheels are chosen as the attitude control system for the spacecraft due to its finer minute control and the longer lifespan of the system that matches or may even exceed the life span of the spacecraft, ensuring operation throughout the entire mission.

G. Scientific Instruments and Payload

Spacecraft are provided with various instruments to observe and predict solar weather coming from the sun, focusing on effects that may damage equipment or harm astronauts near Earth and Mars. The Plasma Magnetometer (PlasMag) "measures solar wind activity" consisting of a Faraday cup and a top-hat analyzer [4,9]. An energetic particle detector measures particle species, energy spectrum, particle intensity (flux), and direction of high-energy particles to determine potential for radiation damage to equipment and astronauts with a suprathermal electron and proton detector (STEP) and an electron proton telescope (EPT) [5]. Charge-coupled devices, combined with specialized telescopes equipped with visible light, Lyot coronagraph, extreme ultraviolet imager (EUV), and narrowband H-alpha capabilities (a narrowband interference filter), and the EPT measure all types of solar weather phenomena [6].

These telescopes include a small aluminum and silicon-carbide Ritchey-Chrétien telescope integrated with an internal Lyot coronagraph and H-alpha narrowband filter (proven on the Hubble and LORRI missions) and a compact EUV telescope imager (better imaging capabilities and flexibility compared to a grazing-incidence) [13,14]. A machine learning (ML) algorithm would be trained on Earth using solar weather data from the SOHO, Solar Dynamics Observatory, ACE, and other similar missions. This would develop a hybrid physics model and the proper framework for ML in this capacity [17]. Next, the algorithm would be split into two 'phases.' The light version would be placed onboard the satellites and be utilized for event detection, training, and weather alerts. The heavy version would do the bulk of the work on Earth with all collected data, comparing it to all previous data, looking for patterns to create solar models and improving long-term weather predictions. All instruments selected for this mission are either very similar to previous NASA and ESA missions or are already flight proven. Instruments will be radiation hardened wherever possible.

H. Components

These satellites will include inertial measurement units, attitude determination and control systems composed of star trackers, sun sensors, reaction wheels and thrusters. Other components include optical line of sight sensors, radiometric tracking capabilities (transmitters and oscillators), and temperature threshold and thermal regulation sensors [7]. All electronic components would be radiation hardened and must be previously proven on NASA, ESA, and other space weather missions.

I. Power Systems

For our solar panels, we opt to use the same solar arrays used by the Venus Express program. The Venus Express was capable of generating 1100 Watts in Venus's orbit with its solar panels. These solar panels will be the main source of energy for our spacecraft throughout their mission life. While the Venus Express had a mission life of only eight years, its solar panels remained functional and reliable and were tested to ensure that they could survive extreme heat cycles while in Venus's orbit [10].

In addition to power production, power storage is also a necessary requirement. We will use lithium-ion batteries to satisfy this requirement. To decide which type of battery to use, reliability was the primary consideration. With a mission life of 15 years at minimum, it is critical to ensure a reserve of power available to each spacecraft at all times. Each spacecraft will have two small batteries onboard, rather than a single large battery for redundancy. Lithium-ion batteries have proven themselves in space applications over the years in a multitude of different environments, including high-temperature missions [18]. Additionally, their high-power density allows for an efficient tradeoff between mass and energy. Our spacecraft will be stable at the Sun-Venus L4 and L5 Lagrange points and will not encounter significant durations of eclipse. As such, the main purpose of our batteries will be to supplement the solar arrays during periods of high-power draw. In the event of a loss of power from the solar arrays, the battery should provide at least six hours of backup power to the essential communication systems.

J. Thermal

The main Thermal Protection Systems (TPS) for our spacecraft are Reinforced Carbon-Carbon composites (RCC), white paint, multi-layer insulation (MLI) and radiators, as well as purposeful instrument and component arrangement. These systems have been proven to withstand the heat of the Sun and will be facing the Sun at all times to regulate the temperature of the satellites [14]. This system is designed to withstand temperatures over 200°C.

K. Structure

The structure of the satellite will be constructed of aluminum using a honey-comb structure. Whipple shields and bumpers are employed to mitigate damage from micro-meteoroids or space debris (MMOD). A multilayer structure of Al-$CaWO_4$ polymer composite-Al is employed to mitigate effects of radiation to internal components. Given that solar radiation is the primary environmental hazard, the team is inspired by ESA's Solar Orbiter and NASA's Parker Solar Probe in terms of component layout.

L. Communications

To satisfy the primary objective of maintaining near-constant communication to Earth and Mars, a dual-satellite communication architecture is proposed. This requires two spacecraft as a redundancy factor mitigating the communication blackouts that each spacecraft will experience during solar conjunction or solar elongation angles below 2.3°. This allows for constant communication without significant signal degradation, as the two satellites will not experience blockages from the Sun or any other body.

The satellites will communicate using the X-band radio frequency (RF) band to transmit high volumes of data to Earth ground stations and Mars communication assets. Each will be equipped with high-gain antennas (HGAs) to support downlink. However, when one of the spacecrafts cannot communicate to Earth or Mars, mission data will be relayed to the second satellite, maintaining continuous communication. The satellites will require two HGAs each to allow for crosslink.

For downlink redundancy and primary uplink communication, both satellites will also include low-gain antennas (LGAs) in the UHF RF band. The LGA system will act as a redundant communication method if the HGA system fails and will handle all uplink between satellites and the ground stations.

V. Financial

The launch costs of our satellites utilizing SpaceX will be about $148 million using two Falcon 9 launches, each costing $74 million. The operations cost will be approximately $12,192,768 and the manufacturing costs will be approximately $150 million. The assembly costs will be approximately $60 million. and the testing costs will be approximately $30 million. SPOT will require approximately $400 million for its entire mission lifetime.

VI. Technical Challenges and Conclusion

M. Major Technical Challenges

This mission is heavily dependent on the integrity of SPOT's radio communications systems; should the spacecraft be unable to transmit its observations due to the high signal noise temperature, this mission fundamentally fails. To curtail the risk of losing data due to free-space loss, the team may investigate the use of optical communication. Optical communication seems promising due to the success of the Psyche mission in 2023.

N. Unique Features

The unique feature of this mission is the utility of being in Sun-Venus L4 & L5, as these points move in an approximately circular heliocentric orbit, allowing SPOT to observe solar phenomena at a consistent quality. Being at the L4 and L5 points provide a minimum-120° arc where the satellites are advantageously positioned to provide critical information of radiation events to Earth at best latency. The ML algorithm being split up into a 'light' alerts and training version on SPOT and the 'heavy' algorithm on Earth to do the heavy lifting helps create predictive models for forecasting.

O. Potential Impact

The impact this mission may have is that SPOT, if successful, could bolster confidence in additional mission programs drawn up to deposit more spacecraft in the L4 and L5 regions of various planetary systems. This could culminate in an initiative to establish useful communication relays that would enable advanced Earth-independent navigation and positioning in deep space, as well as serving as cascading high-bandwidth, high-reliability forwarding and returning links from planet to planet. This may also serve to enable further development of other deep space-infrastructure projects within the L4 and L5 regions.

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