Solar Orbital Logistics and Forecasting Radiation Module (SOLFARM)

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ABSTRACT

SOLFARM is a Mission of Opportunity (MOO) to take advantage of the Gateway as an existing platform to study various aspects of space weather, as well as provide a platform for monitoring space debris via a unique vantage point from the Earth-Sun L4 point. The module will be a shared mission, with the first two phases of its Concept of Operations (ConOps) primarily focusing on a logistics mission to provide the Gateway with necessary supplies. In the second, third, and fourth phases, the module will monitor space weather and quantify the radiation environment at various points in space. In the fourth phase, the module will have a unique view that could prove beneficial for monitoring space debris. SOLFARM’s ConOps will be as follows:

- Phase I: Launch and transit. This phase includes the launch and transit time in route to the Gateway, during which no SOLFARM-specific activities will take place so that power and communications capabilities can be directed towards rendezvous with the Gateway.
- Phase II: Docked with the Gateway. During the module’s time with the Gateway, SOLFARM will begin its studies of space weather to compare the effects of the Earth and the effects of the Moon on space weather events.
- Phase III: Entering the disposal orbit. During this phase, the module will make the transfer from its near-rectilinear halo orbit around the Moon with the Gateway to its disposal orbit, which is a Lissajous orbit around the Earth-Sun L4 point.
- Phase IV: Monitoring space weather. With the module in its disposal orbit, the primary focus of SOLFARM will be detecting space weather events and relaying collected data to the ground station. SOLFARM will also use its vantage point and existing communications capabilities to monitor space debris.

SOLFARM will orbit in a Lissajous orbit about the Earth-Sun L4 point. This viewpoint is particularly advantageous for monitoring space weather, because it is far enough away from Earth that satellites in a variety of closer orbits can be viewed. As the Earth rotates and SOLFARM maintains its position, even satellites in geosynchronous orbit can be monitored. SOLFARM’s remaining mass, power, and communications capabilities are sufficient to include equipment to image these satellites while still accomplishing its logistics mission and its space weather mission. By incorporating a system to monitor space debris into an already-existing platform, the cost of the mission is greatly reduced. The only direct cost to monitoring space debris using SOLFARM is the cost of the equipment. The fuel cost for SOLFARM is calculated based on the maximum mass capability of the module, and because the equipment to monitor space debris is already constrained by that value, there is no added fuel cost. SOLFARM provides the platform to study space debris from a bird’s eye view of the Earth, and as a MOO, takes advantage of a low-cost system to do so.

1 BACKGROUND

The National Academy of Science’s 2013 Decadal Survey on “Solar and Space Physics: A Science for a Technological Society” states the importance of heliophysics and developing the tools necessary to accurately predict space weather [1]. This is increasingly important as astronauts venture towards Mars, as space weather events can increase radiation exposure for astronauts and for technological equipment. Specifically, the Decadal Survey (DS) identifies four science objectives:

1. Determine the origins of the Sun’s activity and predict the variations of the space environment.
2. Determine the dynamics and coupling of Earth’s magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs.
3. Determine the interaction of the Sun with the solar system and the interstellar medium.
4. Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe.

The Living With a Star (LWS) mission is suggested as an integrated way to study solar interactions with the magnetosphere and the ionosphere, thermosphere, and mesosphere (ITM) system. The DS specifically mentions the need for multiple satellites that “provide simultaneous measurements from broad regions of space (so as to be able to separate spatial from temporal effects and reveal the couplings between adjacent regions of space)”. The GDC is NASA’s next approach to the LWS mission, as recommended by the DS [1]. The goal of the GDC is to provide a global network of satellites that will gather data for models of major physical processes, including space weather predictions. A conceptual layout of this global network can be seen below in Fig. 1.

![Global network of satellites](image)

Figure 1: Global network of satellites [2]. The GDC will have satellites to cover much of the Earth, so that the differences in effects of an event such as a solar flare at different points in the magnetosphere and the ITM system can be measured.

SOLFARM will accomplish the goals of the DS by providing an additional platform to study space weather in a different region of space than will be covered by the GDC. While SOLFARM is with the Gateway, the network of satellites providing measurements will reach beyond Low Earth Orbit (LEO), where the GDC-specific satellites will be located. Once the logistics operations of the module have been completed, SOLFARM will leave the Gateway and is assumed to enter into a heliocentric disposal orbit. So, SOLFARM will provide data on space weather in its orbit around the moon and then also in its orbit around the Sun.

2 CONCEPT OF OPERATIONS

The Concept of Operations (ConOps) for SOLFARM can be divided into four phases, seen in Figure 2:

- **Phase I: Launch and transit.** This phase includes the launch and transit time in route to the Gateway. SOLFARM instrumentation will record data throughout this time, so the effects of various parts of Earth’s ITM system on solar weather can be quantified. SOLFARM-specific activities can be turned off if needed to direct power and communications capabilities towards rendezvous with the Gateway, and resumed in Phase II.
- **Phase II: Docked with the Gateway.** During the module’s time with the Gateway, SOLFARM will begin its studies of space weather to compare the effects of the Earth and Moon on space weather events.
- **Phase III: Entering the disposal orbit.** During this phase, the module will make the transfer from its near-rectilinear halo orbit (NRHO) around the Moon with the Gateway to its disposal orbit, which is a Lissajous orbit around the Earth-Sun L4 point.
- **Phase IV: Monitoring space weather.** With the module in its disposal orbit, the primary focus of SOLFARM will be detecting space weather events and relaying collected data to the ground station.
Figure 2: SOLFARM ConOps. SOLFARM ConOps will begin with launch from Earth, include the module’s time on the Gateway, and extend to its transit to and mission at the Earth-Sun L4 point (figure not to scale).

3 SCIENTIFIC EQUIPMENT

Included on SOLFARM will be the following equipment, with metrics shown in Table 1:

- **Scintillator array**, for characterizing the space weather environment through monitoring GCRs. This is described in detail in the Scintillator subsection below.

- **X-Ray sensors**, for monitoring solar activity in the x-ray wavelengths, specifically providing information on solar flares and other solar particle events that could interact with the ITM system and potentially penetrate parts of the atmosphere and magnetosphere [6].

- **Radiometer**, for determination of the radiation environment in SOLFARM’s orbit with the Gateway and in its heliocentric disposal orbit [3].

- **Magnetometer**, for long-term measurement of magnetic field [4]. Magnetometers are included in the DS recommendations for the GDC [1].

- **Thermal ion imager and Langmuir probe**, for measuring ion and electron temperature, ion density, electron density, and ion incident angle [5].

- **Ion velocity meter**, for measuring the velocity of charged particles. This could also include a retarding potential analyzer and an ion drift meter [7]. This is recommended by the DS for the GDC to measure ion characteristics [1].

- **Neutral wind meter**, for measuring the same things as the ion velocity meter but for uncharged particles, which was included in the DS recommendations for the GDC to measure characteristics of neutral particles [8, 1].

Table 1: Resource requirements of the scientific equipment included on the SOLFARM module. As seen by the total mass and power requirements, this easily fits the capabilities of the logistics module.
The end goal of this equipment is to measure GCRs beyond Earth’s atmosphere. This will allow characterization of the space weather environment beyond Earth, so that the risk to a manned vessel can be determined in order to identify effective methods of radiation shielding.

Specific instrumentation is open to new improvements in technology and evolving mission requirements. As the GDC nails down the instruments selected for its satellites, SOLFARM can easily adopt the same instrumentation to ensure that the data collected from SOLFARM complements the data collected from the GDC. As stated in the project description, the provided capabilities of the logistics module include up to 500 kg and 250 W available for science experiments. Table 1 shows that SOLFARM is significantly under budget in mass, requiring a total payload mass of 78.28 kg. It meets the power allotment at 246 out of 250 W. The scintillator array can be adjusted by reducing the number of scintillators to leave resources available for additional instrumentation to be included on SOLFARM to further space weather forecasting abilities as the necessary technology is developed. Additionally, it allows for any changes in power usage that could occur from matching the instrumentation of the GDC as that information becomes available.

## 4 EXPERIMENTS

### 4.1 Phase I

In Phase I, SOLFARM will collect data throughout the module’s launch and transit to the Gateway. Although some data collected from equipment such as the magnetometer may be corrupted by the drastic changes in velocity and acceleration that take place during launch, the space weather information gathered by the remaining instruments will be useful in determining the specific effects of various parts of the ITM and magnetosphere as the module moves through them. To conserve power and communications capabilities, the instrumentation that cannot collect uncorrupted data during launch can be turned off as necessary. Additionally, SOLFARM will retain the ability to turn off each piece of equipment remotely in order to direct power and communication capabilities to rendezvous with the Gateway as needed, and resume measurement activities in Phase II.

### 4.2 Phase II

The Gateway will orbit the Moon in a NRHO. While docked with the Gateway in Phase II, SOLFARM will use this orbit’s vantage point of the Sun to study solar weather events and begin monitoring orbital debris visible from its orbit with the Gateway. Specifically, the effects of solar weather events such as changes in the solar wind can be studied from the NRHO with minimal effects of the ITM and the magnetosphere. Effects of the Moon on solar weather events can then be quantified and compared to those of the Earth.

SOLFARM’s position with the Gateway also provides a unique opportunity to simulate the radiation environment on an asteroid or exoplanet that lacks an Earth-like atmosphere. The Moon’s incredibly thin atmosphere is called a surface boundary exosphere, which is characterized by a very low density of gaseous particles. This low density means that the particles rarely collide with each other, causing the path of the molecules to be determined by the Moon’s gravity and their kinetic energy remaining from when the particles became part of the exosphere [12]. Very little is known about surface boundary exospheres and their interactions with solar radiation. One idea as to the

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Mass (kg)</th>
<th>Power (W)</th>
<th>Volume, if available (mm)</th>
<th>Technology Readiness Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scintillator array (7)</td>
<td>0.6</td>
<td>175</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>X-ray sensor</td>
<td>30</td>
<td>40</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>Radiometer</td>
<td>2.63</td>
<td>5.6</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>Magnetometer</td>
<td>1</td>
<td>1</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>Thermal ion imager</td>
<td>35.7</td>
<td>12.4</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>Ion velocity meter</td>
<td>4.25</td>
<td>2.5</td>
<td>279.4 x 157.5 x 121.9</td>
<td>7</td>
</tr>
<tr>
<td>Neutral wind meter</td>
<td>4.1</td>
<td>9.5</td>
<td>Sensor: 160 (diameter) x 190 Electronics: 220 x 120 x 100</td>
<td>9</td>
</tr>
<tr>
<td><strong>Total:</strong></td>
<td><strong>78.28</strong></td>
<td><strong>246</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
formation of the Moon’s exosphere points to solar wind particles and other high-energy particles that are a part of SOLFARM’s measurements as the source of the exosphere; this idea states that the high-energy particles either knock atoms from the lunar surface, forcing them to become part of the exosphere, or undergo chemical reactions with the lunar surface, leaving the products of the reaction to become the exosphere [13]. SOLFARM could provide valuable information on the radiation environment around the Moon, to indicate whether such high-energy particles are present. If they are present, it would provide support for this idea and could even indicate that the Moon’s exosphere is still being formed, as it would continue to be bombarded with high-energy, exosphere-producing particles.

The model for surface boundary exospheres itself would be improved by SOLFARM’s contributions to quantifying an exosphere’s interactions with space weather. As the module quantifies the Moon’s effects on the radiation environment, that information can be extended to other objects in space that also have a surface boundary exosphere. As this type of atmosphere is predicted to be the most common atmosphere in space, this information has far-reaching consequences [12]. The data gathered by SOLFARM in Phase II could be applied to study the interactions that Mercury, large asteroids, and various moons and planets have with space radiation. Surface boundary exospheres are predicted to be present in objects with a gravitational field comparable to or less than the Moon’s gravitational field [14]. So for the vast number of objects in space for which this is true, including asteroids and other moons and planets, the effects of radiation on this type of atmosphere can be studied.

4.3 Phase III

In Phase III, SOLFARM will enter into a heliocentric disposal orbit upon completion of the logistics mission of the module. The module will enter into orbit at the Earth-Sun L4 point as shown in Fig. 3. The L4 Lagrange point leads the Earth in direction of orbit, and remains approximately two months ahead of Earth in its orbit around the Sun [15]. This is useful in space weather forecasting, as it could detect changes in GCR flux or other things that the Earth might soon encounter in its orbit around the Sun. This orbit will allow for direct communication with ground sites on Earth while still providing a unique perspective for solar weather events, as most satellites observing solar weather parameters are in orbits closer to Earth, like LEO [15]. While an orbit at the L4 point has more risks than an orbit closer to Earth, this different satellite placement will allow for solar weather parameters to be studied without the effects of the Earth’s ITM system. Although L4 is a stable Lagrange point, a satellite cannot sit directly on a Lagrange point. So, SOLFARM will enter into a Lissajous orbit about the L4 point. The selection of a stable Lagrange point and a Lissajous orbit with a small amplitude will decrease the amount of adjustments and therefore minimizes the cost needed to maintain the disposal orbit [15].

Figure 3: SOLFARM’s orbit at the L4 point. SOLFARM will orbit in a Lissajous orbit (left) around the Earth-Sun L4 point (right).

Because the instrumentation onboard SOLFARM is intended to measure space radiation coming from all directions, the specific attitude of the module is not important. As the module orbits in its Lissajous orbit, the direction that each instrument faces will change, and each instrument will therefore be open to collecting data coming from
different directions in space. This allows for characterization of the radiation environment in all directions, instead of maintaining a specific attitude that could exclude collection from a specific region of space.

The radioluminescent material inside the scintillators require a specific crystallographic orientation in order to fully utilize the optical properties of the crystal [16]. By allowing the attitude to change as the module orbits in its Lissajous orbit, there is an increased chance of reaching the proper alignment with the incoming radiation to measure the radiation. Setting a specific attitude for the module would assume a knowledge of the direction of radiative flux, and neglect the fact that radiation can come from any direction in space.

4.4 Phase IV

One specific application of SOLFARM in its disposal orbit, in Phase IV, is to study the Hale cycle. It has been documented that certain solar weather parameters like the number of sunspots follow the Hale cycle, but the reason this happens is unknown [17]. SOLFARM will investigate the 22-year cycle seen in some solar wind parameters by measuring the variation in heliospheric magnetic field (HMF) strength, the radiation levels from solar particle events, and the GCR levels [18]. SOLFARM’s position in a heliocentric disposal orbit will allow for a unique perspective of these events, as well as provide a platform to compare the measurements obtained away from the Earth with those obtained by the GDC and other near-Earth or on-Earth platforms. In this way, SOLFARM will investigate the effects of the ITM system on these solar weather parameters. Additionally, SOLFARM can help characterize the solar weather events that are directed towards other sections of the solar system and do not reach Earth. By using an orbit at the L4 point, SOLFARM can detect events that would go undetected by sensors on Earth and in LEO. There is already significant research on the relationship between changes in the HMF and the amount of GCRs that reach Earth [18]. So, SOLFARM can be used to further enhance experiments done on Earth by providing information on GCR levels and HMF changes without the effects of Earth’s ITM system.

The extra mass and power onboard SOLFARM could be used for military or communications purposes, to fully utilize the unique vantage point given by a satellite in orbit at L4. For example, this orbit will give a bird’s eye view of the satellites orbiting Earth in various closer orbits, and as the Earth rotates, even satellites in geosynchronous orbits could be monitored. One specific use of this vantage point is for monitoring space debris. Because even satellites in geosynchronous orbits can be imaged from the L4 point’s bird’s eye view, the satellites collecting in each of the various graveyard orbits can be monitored. In this case, some of the scintillators in the array could be removed, and the extra mass and power of the module would go towards imaging equipment that would require the ability to rotate and move to maintain a view of Earth, in order to account for the module’s Lissajous orbit and potentially changing attitude.

5 PROJECT TIMELINE

According to the project guidelines, logistics modules will begin launch to the Gateway in 2024. Due to the high Technology Readiness Levels (TRL) of the instrumentation as shown in Table 1, we project that SOLFARM will be ready for launch in 2024. All instrumentation has a TRL of 7 or above, which indicates readiness for missions in space. The scintillator array being developed for SOLFARM is a combination of already-existing and tested technologies, placed in an array to ensure data collection in a wide range of energies. Because identical scintillators have been used in operational environments but in a different configuration than the one proposed, the scintillator array has a projected TRL of 8, indicating its readiness for launch with SOLFARM in 2024.

Module development beginning in 2020 will allow four years for the research and development to take place in order to fully configure the module, including both the logistics material and the SOLFARM-specific material. This will be sufficient time to develop the module for launch readiness in 2024, meeting the Gateway’s projected timeline.

6 FINANCIAL ANALYSIS

While the team had hoped to use NASA’s Project Cost Estimation Capability tool to create a realistic budget assessment, access to this tool has not yet been granted. For this reason, the budget assessment seen here represents the team’s best estimate of the cost of SOLFARM-specific costs for the module. The costs of the logistics mission of the module are not included, as there was not enough information available pertaining to the projected contents of a logistics module to the Gateway and its intended trajectory. The expected costs for the SOLFARM-specific
activities of the module demonstrate the extremely low-cost approach of this module, coming in at under 0.015% of NASA’s FY19 budget [19]. The estimated cost is shown in Fig. 4.

<table>
<thead>
<tr>
<th>Instrument/Expense</th>
<th>Cost per Unit</th>
<th>Units</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telescope with scintillator</td>
<td>$750,000.00</td>
<td>1</td>
<td>$750,000.00</td>
</tr>
<tr>
<td>X-ray sensor</td>
<td>$10,000.00</td>
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<td>$10,000.00</td>
</tr>
<tr>
<td>Radiometer</td>
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<td>$6,000.00</td>
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<tr>
<td>Magnetometer</td>
<td></td>
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</tr>
<tr>
<td>Thermal ion imager</td>
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<td>1</td>
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<tr>
<td>Ion velocity meter</td>
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<td>1</td>
<td></td>
</tr>
<tr>
<td>Neutral wind meter</td>
<td>$65,000.00</td>
<td>1</td>
<td>$65,000.00</td>
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<tr>
<td>Communications system</td>
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<td>$100,000.00</td>
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<tr>
<td>R &amp; D</td>
<td></td>
<td></td>
<td>$1,000,000.00</td>
</tr>
<tr>
<td>Fuel cost (Delta V)</td>
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<td></td>
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<tr>
<td>Ground control</td>
<td></td>
<td></td>
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</tr>
<tr>
<td><strong>Total</strong></td>
<td>$3,031,000.00</td>
<td></td>
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</tbody>
</table>

Figure 4: Expected SOLFARM-specific costs.

7 CONFORMITY TO NASA’S 2018 STRATEGIC PLAN

In 2018, NASA published a strategic plan for the next four years, focusing on a vision to discover and expand knowledge for the benefit of humanity. The plan includes four strategic goals: to discover, explore, develop, and enable [20]. As seen in Figure 5, SOLFARM clearly conforms to all four of these goals. SOLFARM’s goal is to quantify the radiation environment in various areas of the solar system, including at surface boundary exospheres and at the Earth-Sun L4 point. SOLFARM will encourage the development of effective radiation shielding by providing the necessary information to do so. This in turn will enable astronaut safety across the Solar System.

Figure 5: Demonstration of SOLFARM’s conformity to NASA’s strategic plan.
8 REFERENCES


9 PUBLIC RELEASE CLEARANCE

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