

Article

Spitzer Resurrector Mission: Advantages for Space Weather Research and Operations

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Abstract: In 1979, NASA established the Great Observatory program, which included four telescopes (Hubble, Compton, Chandra, and Spitzer) to explore the Universe. The Spitzer Space Telescope was launched in 2003 into solar orbit, gradually drifting away from the Earth. Spitzer was operated very successfully until 2020 when NASA terminated observations and placed the telescope in safe mode. In 2028, the U.S. Space Force has the opportunity to demonstrate satellite servicing by telerobotically reactivating Spitzer for astronomical observations, and in a separate experiment, carry out novel Space Weather research and operations capabilities by observing solar Coronal Mass Ejections. This will be accomplished by launching a small satellite, the Spitzer-Resurrector Mission (SRM), to rendezvous with Spitzer in 2030, positioning itself around it, and serving as a relay for recommissioning and science operations. A sample of science goals for Spitzer is briefly described, but the focus of this paper is on the unique opportunity offered by SRM to demonstrate novel Space Weather research and operations capabilities.

Keywords: space weather; Spitzer; astrophysics



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1. Introduction

Space Weather (SWx) is a serious concern for all areas of our society, yet forecasting remains an extremely challenging problem. The size and complexity of the system (inner heliosphere) compared to the size of Earth—the ‘target’ of the forecast—is enormous (about >108:1 in area). Observing the system with only a handful of research missions results in sparse coverage and inconsistent data over time. Solving the sparse coverage problem is a complex and expensive task that requires a systems approach [1] and efficient collaboration among the government, military, and commercial sectors, as has been noted in several recent reports (e.g., SWx R2O2R Framework [2], NAS Workshop on the Future SWx Research & Operations Infrastructure [3]).

An obvious strategy to build up the SWx space infrastructure is to leverage the increasing number of launches via rideshares (e.g., NOAA’s SWFO-L1 on the NASA IMAP mission). While this strategy is gaining popularity, with several rideshare missions (mostly CubeSats) on the books, it is not the only option. NASA’s planetary missions have long hosted Heliophysics-funded payloads that leverage the cruise phase or orbit to make measurements with Heliophysics science priorities.

This inter-divisional collaboration has been successful in sampling heliospheric regions that would be programmatically difficult to reach otherwise. An example is the Interstellar Mapping and Acceleration Probe (IMAP) mission, which leverages collaboration among

divisions to resolve scientific questions about the heliosphere. So, why not replicate this strategy across more government agencies including the Department of Defense (DoD) as well as the commercial sector? Dual-use instrumentation is already considered for GEO and LEO DoD missions. Can we expand this to Deep Space where our observational coverage needs are severe? Those programs, however, are expensive and thus have long development schedules preceded by cumbersome and complex acquisition procedures. Could we come up with a more agile response that lowers costs and, importantly, speeds up the observational coverage in Deep Space?

In the following, we describe a potential pathfinder opportunity to answer these questions in the affirmative. The Spitzer-Resurrector Mission (SRM) concept leverages an unusual funding opportunity, an interdisciplinary team from academia and industry, a novel mission design, and recent research and technical advances in Heliophysics to reach a cost-effective, yet innovative, solution to both research and operations gaps in SWx.

2. Mission Objectives

The Spitzer-Resurrector Mission (SRM, hereafter) is a space mission concept which recently underwent a Phase I study funded by the U.S. Space Force (USSF) under the Orbital Prime [4] call. SRM is ‘two missions in one’, with goals of demonstrating spacecraft recovery and control in deep space, as well as demonstrating novel SWx research and operations capabilities. The spacecraft recovery is accomplished by launching a small satellite to rendezvous with the Spitzer Space Telescope [5] (currently in hibernation) in 2030, positioning itself around it, and serving as a relay for recommissioning and science operations is discussed in Section 3.

The on-orbit servicing objectives of SRM have long-term benefits (lower risk, higher science return) for space missions in the future. A sample of science goals for Spitzer is described in Section 2.1. However, the focus of this paper is on the unique opportunity offered by SRM to demonstrate novel SWx research and operations capabilities, highlighted in Section 3.2.2.

2.1. SRM-Science Objectives

During the Phase I study we are considering several payload options (Section 3.2) to demonstrate the versatility of the mission and spacecraft design to SWx objectives. Each instrument brings a unique measurement capability that can fill important gaps in our scientific knowledge while offering novel Research-to-Operations pathways with benefits to USSF, NOAA, NASA, and various other U.S. federal agencies. Figure 1 depicts the expected imaging capabilities of SRM for tracking CMEs. The final payload mix will depend on sponsor and schedule priorities. Our list of technical and research objectives, along with the measurement approach for each, is as follows:

- Demonstrate remote sensing and reconstruction of CME magnetic fields (Faraday rotation);
- Understand the evolution of CME plasma and magnetic field in the inner heliosphere (Imager, Faraday rotation);
- Improve solar energetic particles (SEP) time-of-arrival, peak, and fluence predictions for cislunar space (SEP suite);
- Improve CME time-of-arrival predictions (Imager, Faraday rotation);
- Test real-time monitoring of solar wind impacting Earth (Imager, Faraday rotation);
- Improve forecasting of CME and SEP events (Imager, SEP suite).

The main goal of SRM is to demonstrate satellite servicing by establishing radio contact with Spitzer, verifying its health, relaying command sequences to restart its operations, and then remaining nearby to act as a communications relay so that Spitzer can resume operations. With SRM, Spitzer will be much more efficient than it was at the end of its mission because it will no longer have to pause observations for hours-long downlinks to transfer data. The potential Spitzer/Infrared Array Camera (IRAC) observations are complementary to JWST’s capabilities because IRAC’s wide field of view and Spitzer’s

rapid pointing enables it to map large areas of the sky much more quickly than JWST. In addition, it can monitor many individual objects, such as active galactic nuclei or young stellar objects, for variability. Long continuous observations are also possible, such as the continuous 21-day Spitzer observations of the Trappist-1 exoplanet system. Finally, Spitzer's unique location in the solar system, in conjunction with earth-based telescopes or JWST, EUCLID, or Roman Space Telescope observations, enables microlensing parallax observations that can determine the mass and distance of free-floating planets and exo-moons.

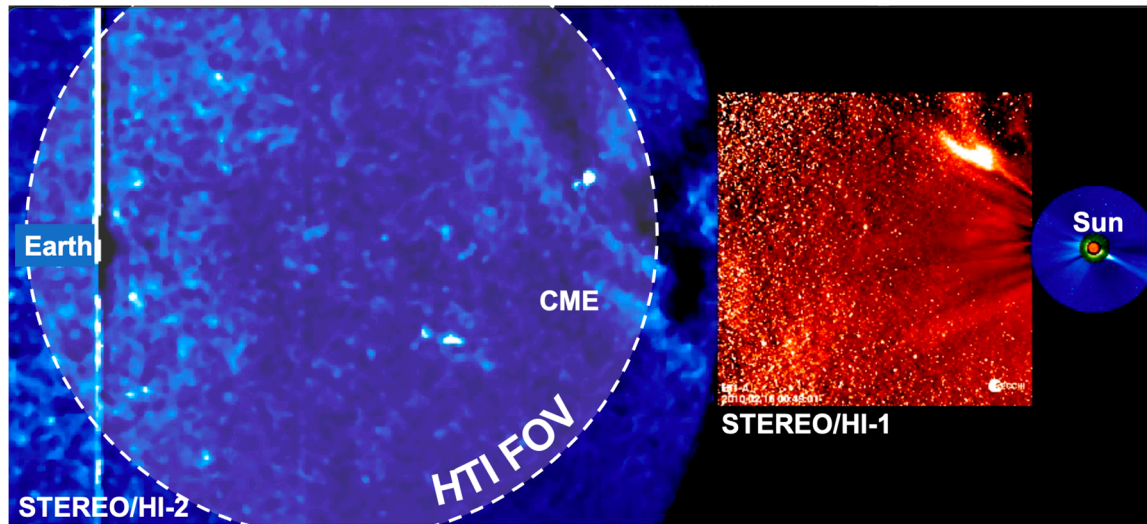


Figure 1. This snapshot of an Earth-directed CME on 16 February 2010 was captured by the imagers on STEREO-A from the Lagrangian L4 region. The SRM Imager (FoV is marked) can acquire images $\sim 10\times$ higher contrast and $4\times$ higher spatial resolution than HI-2 thanks to its vantage point and larger aperture while leveraging the designs matured in Parker Solar Probe and Solar Orbiter missions.

Spitzer's location also makes possible observations of potentially hazardous asteroids that are currently not observable from near-Earth instruments. The science program proposed for the resurrected Spitzer will be described more fully in a future paper [6], in preparation.

3. Mission Design

3.1. Orbit, Trajectory Past Earth-Sun L4, and Station-Keeping near Earth-Sun L3

After a launch as a ride-along on an Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) ring to lunar transfer orbit, the spacecraft uses electric propulsion to achieve the necessary Δv . The SRM trajectory, shown in Figure 2, comprises one year of thrusting to descend to 0.875 AU, coasting for roughly a year and a half, and then another year of thrusting to raise its orbit to $1.023 \text{ AU} \times 1.003 \text{ AU}$. The total transit time from the Lunar Transfer Orbit (LTO) to the final destination is approximately three and a half years.

This course takes Resurrector in front of the west side of the Sun, which is relevant for space exploration due to the magnetic connection of eruptions on this hemisphere to the Earth-Moon system. Station keeping near the Earth-Sun L3 point allows continuous beaconing to characterize solar flow and perform real-time CME detection using an Earth-based ground aperture. In addition, simultaneous helioimaging is performed to augment the radio beacon data.

The far-side location near L3 also allows Resurrector to rendezvous with and restore operations to the Spitzer Space Telescope, placed in safe mode in 2020. The spacecraft allows a two-for-one mission in space weather and spacecraft servicing/recovery.

The trajectory necessitates long-duration continuous burns of one or more ion thrusters. A multi-thruster version would allow differential thrusting to simplify the propulsion

system by eliminating the need for a gimbal and tankage while simultaneously using a compact, scalable thrust array. Substantial Δv is possible using such an array, up to 6 km/s depending on the overall mass of the spacecraft.

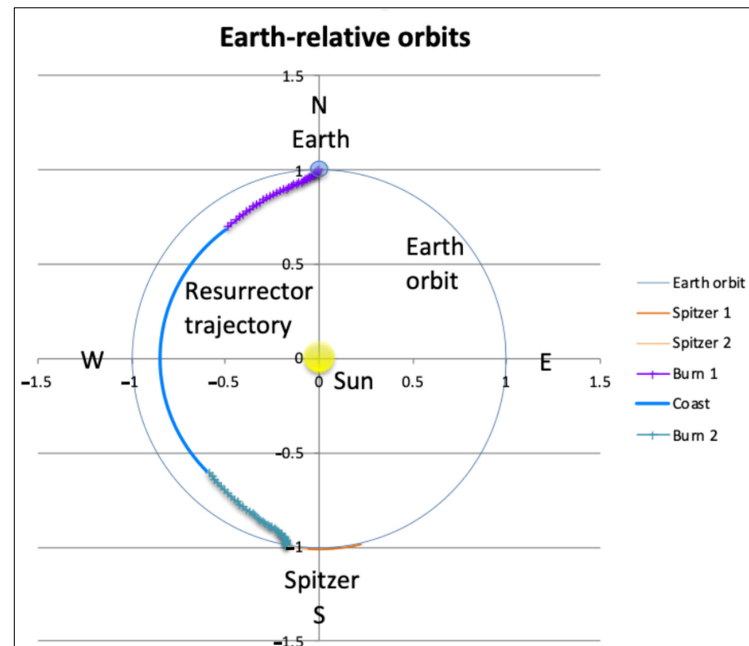


Figure 2. The trajectory of the Resurrector past the western hemisphere of the Sun before arrival near Earth-Sun L3.

3.2. Strawman Payloads

3.2.1. Heliospheric Transient Imager (HTI) Image

HTI is a modified version of the WISPR instrument [7] aboard the Parker Solar Probe mission, currently in operation. WISPR looks at the large-scale structure of the corona and solar wind, like CMEs. HTI retains the WISPR camera electronics box, baffle system, and Inner Telescope, repackaged into a smaller volume for imaging within 5° from the Sun (Figure 3). The current volume of 25 cm $\times$ 40 cm $\times$ 15 cm (H $\times$ L $\times$ D) will be reduced through further optimization. Based on the current on-orbit performance of WISPR, we conservatively estimate that HTI will be $\sim 2\times$ more sensitive than STEREO/HI-1 and $>10\times$ more sensitive than STEREO/HI-2.

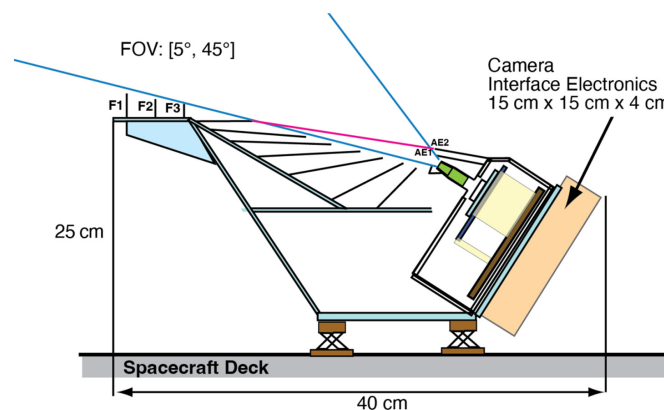


Figure 3. Side view of the WISPR instrument showing the exterior (F1–F3) and interior baffles (AE1, AE2). The HTI is a modified version of the WISPR instrument on PSP capable of observing within 5° from the Sun's center. HTI will perform $>10\times$ better than STEREO/HI-2 for the same solar elongations.

3.2.2. Faraday Rotation Experiment (FRE)

When linearly polarized radiation transverses magnetized plasmas, it undergoes rotation in its polarization plane. This effect, dubbed Faraday Rotation (FR) has been used for decades to remotely probe coronal and heliospheric structures (e.g., Levy et al. 1969 [8]; Kooi et al. 2017 [9]; and Figures 4 and 5). FR is a particularly promising remote sensing technique to derive not only the strength but also the 3D configuration of the magnetic field in CMEs while they are still in the corona. This is a valuable capability for SWx operations, as the CME magnetic field is the dominant quantity in assessing a CME's geo-effective potential. The rising interest in SWx impacts across the U.S. civilian and military sectors has renewed interest in FR studies and space applications [10,11].

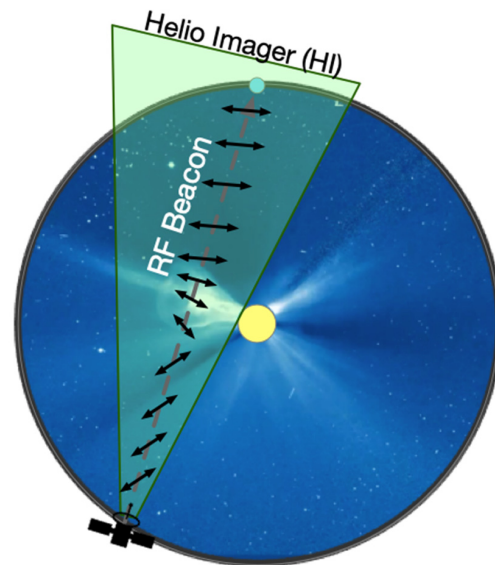


Figure 4. The Faraday Rotation Experiment (FRE) will probe the internal magnetic structure of Earth-directed transients while the Helio Imager provides the large-scale context and density information. FRE transmits an S-band linearly polarized signal that can be received by modestly sized (~15 m) ground stations around the world and used for SWx research and operations.

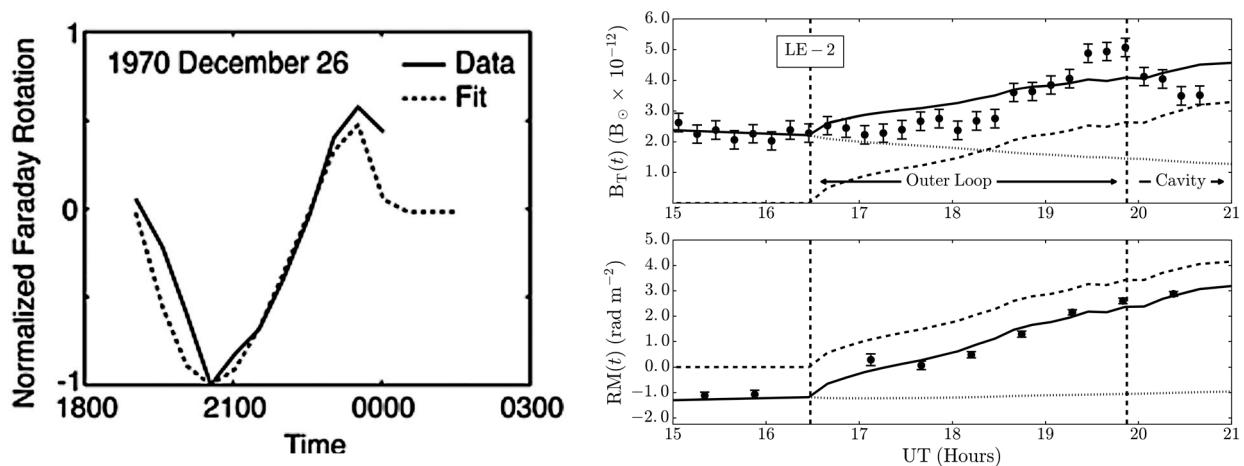


Figure 5. The FRE technique has been proven with both spacecraft transmission (left: Pioneer 4, from Jensen & Russell 2008 [12] ©AGU) and astronomical sources (right: 0842, from Kooi et al. 2017 [9] © AAS).

SRM offers an excellent opportunity to demonstrate the SWx value of the FR technique by deploying a radio experiment specifically designed for FR studies. We baseline a linearly polarized beacon at the X-Band (8.1 GHz) that transmits a prescribed signal pattern (i.e.,

square wave) through the 75 cm high-gain dual-feed antenna (HGA). The dual-feed system can accommodate both the FRE and downlink from the rest of the payload. The signal pattern facilitates calibration, while the relatively large HGA lowers the power requirement for the transmitter. The system requires a straightforward linear polarimeter at the ground station and may not require the use of the DSN. In any case, Ohlson et al. [13] have already demonstrated space-to-ground FR measurements across 1.8 AU with Pioneer 4 using 1970's technology and thus the technical challenges are minimal. During the 3.5-year cruise phase, the HGA is mostly pointed to Earth, except for burns and occasional interruptions for other tests. The FRE beams continuously during this time and allows us to test various techniques for deriving the heliospheric density and magnetic field with the assistance of the HTI observations that provide both context and a line-of-sight density estimate. We will also test and develop methods for ingesting the FRE information into research and operational models of the heliosphere and for developing forecasting workflows with this novel information.

3.2.3. Solar Energetic Particles Suite (SEPS)

The SRM trajectory is ideal for measuring SEPs directed to cislunar space. The data are critical for improving SEP forecasting schemes [14]. The required coverage is given in the NASA Gap Analysis Report (0.1–1 MeV electrons, 0.02–700 MeV protons, and heavy ion composition). Such an SEP package can be formed by spares of recently built instruments on Solar Orbiter and Parker Solar Probe but can also use adaptations of instruments from other missions. An example package that meets these requirements is shown in Figure 6. See [15] for details.

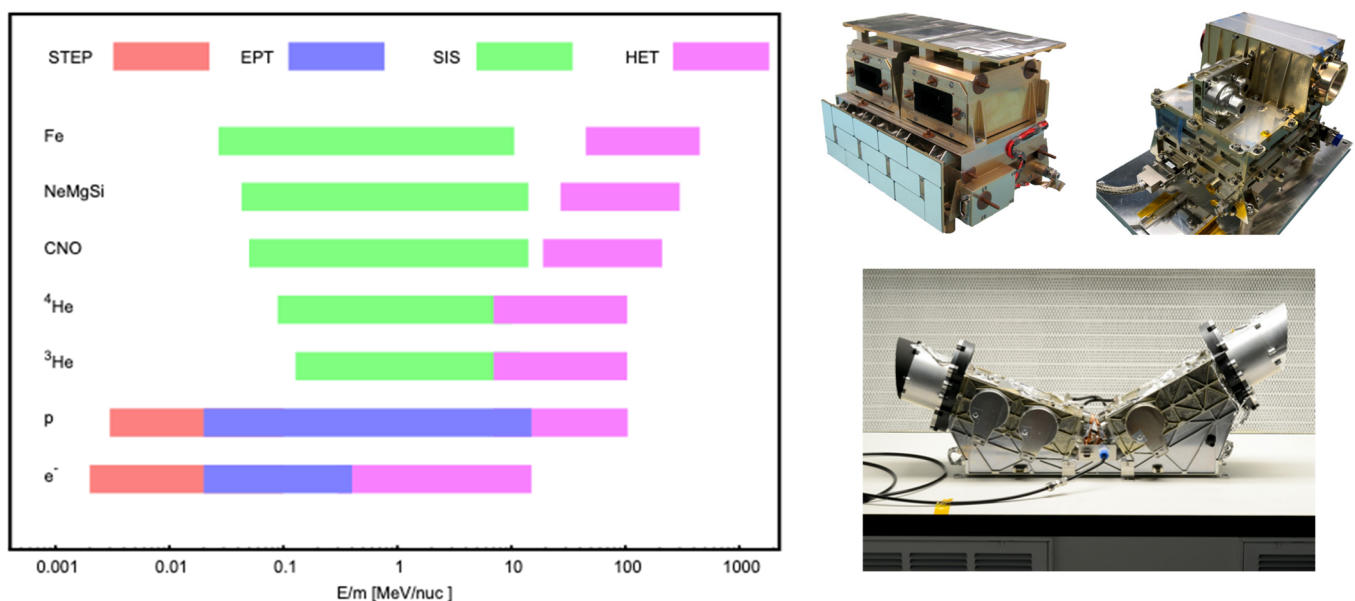


Figure 6. Candidate instrumentation for the SEP suite on SRM. **Left:** energy and ion species coverage of the EPD sensors. **Right:** Pictures of the flight units of STEP (upper left ©A&A), EPT-HET (upper right ©A&A), and SIS (bottom ©A&A) [15].

3.3. Concept of Operations

Resurrector operations are highly autonomous, utilizing onboard optical navigation to fully eliminate radiometric interference and allow the use of non-DSN ground stations like APL's Satellite Communications Facility for data downlink and FRE beacon reception. The spacecraft determines its orbit and trajectory from images taken by its navigation camera of Earth, the Moon, and a variety of asteroids while making its way to the vicinity of L3. This data is fed through a Kalman filter inside the commercialized AutoNav Mark 4 software onboard, solving for the orbit and maneuver modifications to keep its burn on track with

its desired trajectory. Uplink is needed only occasionally, on the order of once per month, to load new background sequences for science gathering and housekeeping.

Upon reaching the vicinity of L3, the spacecraft autonomously completes a pop-up maneuver to place it in the desired location to use its helioimager at a nominal cadence of 30 min and continue transmitting the RF beacon to Earth. The autonomous sequences run the instruments according to a standard plan with observation modes and transmit data to Earth, eliminating the need for most uplink activities. Spacecraft station-keeping is performed using AutoNav Mark 4 software, which also performs onboard navigation relative to the nearby Spitzer Space Telescope.

The Resurrector's second mission of reactivating Spitzer by providing a crosslink and an Earth relay as the telescope comes out of solar conjunction occurs simultaneously with the space weather science operations.

3.4. Technology Development

The Resurrector requires no major technology development for its space weather mission. HTI is a repackaging of the WISPR instrument. The RFE is modeled after the Pioneer 4 beacon but updated with current space-qualified RF components. The SEPS uses TRL-9 design and spares from recently flown instruments. The spacecraft itself uses all TRL-9 off-the-shelf components, from its avionics and power subsystems to its attitude control and propulsion subsystems. Two key advanced software technologies and a key propulsion technology are described below.

3.4.1. Virtual Machine Language Sequencing 3.0 [TRL-9] and AutoNav Mark 4 [TRL-6]

VML 3 [2,16–19] is a commercialized version of the advanced spacecraft sequencing software with heritage back to fifteen missions, including the Spitzer Space Telescope, Mars Reconnaissance Orbiter, Dawn, Mars Phoenix, and OSIRIS-REx. The latest version enables highly advanced autonomous expert systems to operate the spacecraft, including navigation and maneuvering activities produced by AutoNav Mark 4. AN4 is a commercialized version (NASA SBIR 80NSSC18C0043) of the autonomous navigation software AutoNav [20,21] with heritage back to Deep Space 1, Stardust, and Deep Impact.

3.4.2. High Delta-V Maneuvering

Resurrector features a baselined Δv capability of approximately 6 km/s with a 30% margin on board. This is achieved using eight Enpulsion Micro R3 indium-ion propulsion modules, arranged to allow for differential thrust vectoring. Extra Δv allows mission trajectory options and backup for failed thruster modules. Xenon-ion propulsion has also been analyzed as a possible baseline using commercially available thrusters.

3.5. Programmatics

3.5.1. Operational Readiness of Spitzer

At the end of the mission (EOM), Spitzer was fully capable of continuing the Warm Mission [5], with substantial power and propellant margins and a healthy IRAC instrument. The spacecraft is anticipated to be fully operational upon the arrival of the Resurrector in health, power margin, available propellant, thermal stability, and IRAC functionality. Of the two thruster strings, String 2 was nominal. Inertial Reference Unit 1 was slightly degraded but functional, Unit 2 was nominal. The 3.6 μm and 4.5 μm channels of the IRAC instrument used during the Warm Mission were nominal. The transponder was set to carrier-only mode. The spacecraft was left on Side B of the avionics after a solar event, with Side A in reserve. All four Reaction Wheel Assemblies (RWAs) were fully operational.

At EOM, Spitzer was placed into indefinite safe mode in a two-hour rotation about the sunline, pointing its sunshield and solar cells directly normal to the Sun. In this configuration, the only nominal influences on the spacecraft that would affect the need to desaturate the RWAs are solar radiation pressure and precession of the sunline during an orbit, both minor in magnitude. At EOM, nitrogen propellant reserves were 6.674 kg

remaining of an original 15.59 kg load (42%). Power generation at EOM was 12.2 A at 26.3 V for 345 W, with a total of 2015 battery cycles out of a minimum 25,000-lifetime capacity (90% remaining). Expected degradation in power generation by the time the Resurrector arrives places the generated current at 11.9 A (336 W). The Warm Mission is estimated to need 11 A (311 W) for nominal thermal zone profiles, yielding a margin of approximately 8% before taking any power-saving steps for an additional 10% margin.

Power generation is one limiting factor for the lifespan of the resurrected Spitzer. Current models show an expected reduction of 0.0377 A/year, giving Spitzer an additional 24 years of operations before power-saving measures such as turning off heaters in the spacecraft bus would be required. Unexpected incidents like CME damage and micrometeoroid impacts would decrease this timespan.

Another limiting factor is the propellant necessary to desaturate the PCS during nominal operations. In later years, sophisticated planning for pointing the spacecraft in ways that remove momentum inputs from prior turns was adopted to considerably reduce the rate of propellant usage. Assuming a similar conservative approach, the telescope can be expected to operate for an additional ten years or more.

3.5.2. Schedule

SRM is timed for a 2027 launch to rendezvous with the Spitzer Space Telescope in 2030 as the telescope comes out of solar conjunction. The extensive use of off-the-shelf TRL-9 technology and the use of instruments with few changes from previously flown versions help support this schedule (Figure 7). The orbital geometry and nature of the trajectory also easily support later launch dates and arrival times, reducing mission risk due to potential build and launch delays.

Q2 2026	Start of spacecraft integration
Q1 2028	Launch on rideshare to lunar transfer orbit, spacecraft commissioning, EP-1 burn start
L+20 days	Start of space weather mission
L+313 days	Descent to 0.875 AU complete, EP-1 end, continuing space weather observations
L+762 days	Start EP-2 burn
Q4 2030	Arrive at orbit 1.023×1.003 AU, end EP-2, resurrect Spitzer, continue space weather observations
Q4 2032	Complete two years of space weather mission, Spitzer characterization of asteroids, other deep space observations
Q4 2034	Complete additional two years of space weather/asteroid characterization/observations

Figure 7. Spitzer-Resurrector mission timeline.

3.5.3. Rideshare

SRM’s inherent mission timing flexibility, the ESPA-sized spacecraft, and the compatibility of the trajectory with an LTO throw all combine to make SRM an ideal candidate for rideshare opportunities. Rideshares available on NASA, DoD, and commercial launches would dramatically expand opportunities for launch. The potential of in-kind support from interested agencies using this launch mechanism should also be explored.

3.5.4. Cost

Resurrector is designed to be a compact, low-cost, high-capability spacecraft. The entire mission, including launch costs, is targeted at USD 275 M–USD 375 M with 30% reserves. A rideshare arrangement covered by outside sources would reduce this amount to roughly USD 130 M–USD 180 M.

3.5.5. Public/Private Partnership

The currently funded Phase-I of the Spitzer-Resurrector concept has enabled rapid collaboration between space industry stakeholders. The mission as designed achieves advances in space weather experimentation and warning, on-orbit servicing in deep space, planetary defense, and astronomy. This success in leveraging the unique opportunities provided by the mission location can be attributed to mission leadership by a private company, responding to defined requirements and desires of public organizations such as the USSF, NASA, NOAA, and SAO (the Smithsonian Astrophysical Observatory, a partner in the Center for Astrophysics | Harvard and Smithsonian). Rather than any individual public organization proposing and developing a mission in isolation, the private-led effort can move quickly in coordinating stakeholders and find compromises to de-risk future standalone missions. The SRM team already has begun planning for making at least some of the data public and enabling some level of participation by outside experts. Public education and outreach and DEI are important components of the mission.

4. Conclusions

We presented the SRM concept to raise awareness in the community of a non-traditional opportunity to fill in observational gaps in Heliophysics. A tech demo opportunity from the USSF has brought together industry engineers, astrophysicists, and heliophysicists who devised an 'out-of-the-box' response to the call. The resulting concept goes far beyond the USSF's interest in exploring novel on-orbit servicing ideas. It aims for deep-space spacecraft recovery and operations, demonstrates propulsion and on-board autonomy, provides novel SWx measurements for improved forecasting around the Artemis missions, and resurrects an astrophysics mission that could provide critical synergies to JWST and perform planetary protection observations. Yet, for all these exciting aspects, there are equally challenging concerns. For example,

- This is a 'short fuse' opportunity. To provide SWx observations for Artemis III, SRM needs to launch by 2027. This timeline is too short to maneuver through the usual NASA proposal cycle. Our proposed cross-agency government/public/private collaboration has the additional advantage of facilitating rapid procurement of scientific instrumentation, as well as providing quick access to technical, scientific, and public resources;
- SRM-SWx should be of interest to NOAA or others since its operational structure naturally enables innovative participation via 'data buy,' guest observer, and/or other options.

We close with the following suggestions for consideration in the upcoming Decadal Survey discussions, based on our experience with this project:

1. Facilitate information exchange among the various Program Officers of government organizations involved in space projects. For example, being aware of potentially useful calls (or selections) to Heliophysics in other agencies should help with planning across the Division;
2. Consider a 'rapid response' space hardware development program. It could be an agile version of the Mission-of-Opportunity program able to respond to launch/rideshare/host opportunities from other agencies with a short proposal/evaluation cycle (1–2 months, instead of years). DoD experience may be particularly useful for this type of program;
3. Consider co-funding missions/hardware calls with DoD and NOAA so that successful Heliophysics concepts can be developed more efficiently and rapidly;
4. Finalize a 'data-buy' policy and implementation document to engage the space industry in closing the SWx infrastructure gaps in the next decade and beyond.

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