The Sun Radio Interferometer Space Experiment (SunRISE) Mission

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***Abstract*—The Sun Radio Interferometer Space Experiment (SunRISE) will provide an entirely new view on particle acceleration and transport in the inner heliosphere by creating the first dedicated low radio frequency interferometer in space to localize heliospheric radio emissions. By imaging and determining the location of decametric-hectometric (DH, 0.1 MHz–23 MHz) solar radio bursts, SunRISE will provide key information on particle acceleration mechanisms associated with coronal mass ejections (CMEs) and the magnetic field topology from active regions into interplanetary space. The SunRISE Observatory will consist of six space vehicles in a passive formation, in orbits designed to keep them within approximately 10 km of each other, and flying in a supersynchronous orbit, about 400 km or more above geosynchronous Earth orbit (GEO). Each space vehicle consists of a Solar DH-GNSS payload and a 6U form factor spacecraft. The SunRISE Observatory together with significant ground-based processing, will enable imaging of the Sun in a portion of the spectrum that is blocked by the ionosphere and cannot be observed from Earth. Key aspects that enable this mission are that only position knowledge of the space vehicles is required, not active control, and that the architecture involves a modest amount of on-board processing coupled with significant ground-based processing for navigation, position determination, and science operations. Mission-enabling advances in software-defined radios, GPS navigation and timing, and small spacecraft technologies, developed and flown on the DARPA High Frequency Research (DHFR) and the Community Initiative for Continuing Earth Radio Occultation (CICERO) have made this mission affordable and low-risk. The SunRISE mission will exploit the multiple spacecraft per aperture (MSPA) capability of NASA's Deep Space Network (DSN), for more efficient data transfers of larger data volumes, and utilize commercial access to space, in which the SunRISE space vehicles will be carried to their target orbit as secondary payloads in conjunction with a larger host spacecraft intended for GEO.**

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1. INTRODUCTION

Understanding particle acceleration is one of the most urgent Heliophysics challenges, as identified in the *Solar and Space Physics: A Science for a Technological Society* Decadal Survey and other reports from the National Academies for Science, Engineering, and Medicine. The phenomenon occurs in plasmas throughout the cosmos: at stars, at supernova shocks, in magnetospheres, at the termination shock, and in magnetic reconnection. Particle acceleration leads to the creation of solar flares and coronal mass ejections (CMEs), solar energetic particles (SEPs), anomalous cosmic rays from the termination shock, and Galactic cosmic rays (GCRs).

The combination of new magnetic flux emerging through active regions and the differential rotation and motion of the surface of the Sun combine to create coronal structures with complex magnetic field topologies. These structures include large and adjacent closed magnetic loops with opposite polarity or large-scale magnetic flux ropes, such as filaments or prominences. A remarkable discovery of the Space Age is how efficiently magnetic energy stored in the solar atmosphere and corona can be converted into SEPs. Due to its high temperature, the standard electrical conductivity of the solar corona approaches that of a metal, resulting in the classical prediction that magnetic field is effectively frozen into the plasma, with an estimated diffusion time of millions of years. Instead, the corona is able to reconfigure its magnetic field explosively, on timescales of seconds to minutes. This extreme difference between predicted and observed timescale is due to small-scale kinetic plasma physics, which can drastically change dynamical scales and transport rates compared to expectations from classical fluids.

These structures that form in the solar corona represent large departures from the minimum energy state, and, when forces cross a threshold, magnetic reconnection can permit stored magnetic energy to convert rapidly into thermal and kinetic plasma energy as the field relaxes into a simpler state. Broadly speaking, two related classes of events triggered by the explosive onset of magnetic reconnection convert the magnetic energy into plasma energy including SEPs: flares and CMEs. A flare can be considered as an event low in the solar corona that predominantly converts the magnetic energy into kinetic energy, heating the plasma to extreme temperatures and locally accelerating some particles to high energies. A flare can release all of its energy at once, but often a large flare is preceded by tens or hundreds of smaller flares, each of which can accelerate particles to high energies and release them into the heliosphere. In the case of a CME, reconnection leads to heating but also to bulk kinetic acceleration and motion.

The Decadal Survey identified SEPs and acceleration as high priority science not only because of the compelling nature of the science but also because of the direct impact these particles have on society through space weather. SEPs and GCRs can cause electronic equipment, and thereby satellites to fail, and wreak havoc in biological systems leading to cancer and radiation sickness in cases of high levels of exposure (Schwadron et al. [27]). Despite its importance, Heliophysics has not been able to resolve the sources of SEPs or determine how some SEPs are able to quickly spread to a broad range in solar longitudes. Without new measurement methods for SEP sources (Cucinotta et al. [6]; Schwadron et al. [26]), Heliophysics will be missing a cornerstone of the foundation for understanding particle acceleration. Parker Solar Probe (Fox et al. [9]; Kasper et al. [14]) will fly within 10 R_S and measure plasma properties, SEPs, and CMEs, but will not measure particles as they are first accelerated at 2 R_S and higher (Liu et al. [18]; Veronig et al. [32]; Kozarev et al. [16]; Ma et al. [19]).

The SunRISE mission will provide this new approach. SunRISE Mission Formulation (Phase B) began[1] in 2020 June and completed in 2021 September, at which time the Project entered Development (Phase C). This transition from Formulation to Development was marked by NASA's approval for the SunRISE Project to begin constructing flight hardware and proceed to readiness to launch. This paper presents a summary of the Formulation work and the early portions of Development.

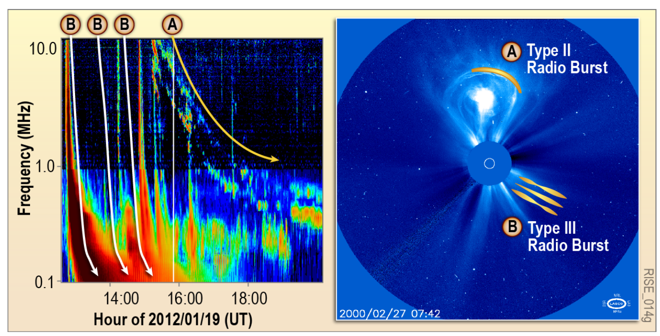

Figure 1. SunRISE uses Type II (A) and Type III (B) decametric-hectometric radio bursts to track particle transport and acceleration within the inner heliosphere. (*left*) The state of the art, a dynamic radio power spectrum from the WAVES instrument on the Wind spacecraft illustrating a storm of Type III bursts preceding a several hours-long Type II burst from a CME. (*right*) Illustration of Type II and III radio bursts in a heliophysics context, showing Type II bursts being produced by a CME (shown here as if they might originate near the nose of the CME) and Type III bursts produced from an electron beam.

2. SCIENCE GOALS

The SunRISE scientific investigation will make use of two well-studied classes of decametric-hectometric (DH) solar radio bursts (Figure 1) produced by electrons energized near

[1] Approval for SunRISE to enter Formulation (Phase B) occurred in a virtual meeting, as a result of the COVID-19 pandemic, and was the first time that Key Decision Point B approval occurred virtually.

expanding CMEs (**Type II**, e.g., Gopalswamy et al. [11]) and by electrons released by solar flares along open field lines (**Type III**, e.g., Wild [33]; Dulk et al. [7]). Tracking Type II and III radio bursts from 2 R_S to at least 20 R_S will allow SunRISE to achieve two compelling science objectives.

Objective 1 is to discriminate between competing hypotheses for the source mechanism of CME-associated SEPs by measuring the location and distribution of Type II radio emission relative to expanding CMEs at altitudes 2 R_S–20 R_S from the Sun where the most intense acceleration occurs. Completion of Objective 1 will reveal where electron acceleration and DH radio bursts occur relative to the overall structure of CMEs, determine if specific properties of CMEs lead to DH radio bursts, and whether the magnetic connection between the location of the radio burst and an observer influences the detection of SEPs in interplanetary space.

Objective 2 is to determine if a broad magnetic connection between active regions and interplanetary space is responsible for the wide longitudinal extent of some flare and CME SEPs by imaging the field lines traced by Type III radio bursts from active regions through the corona. Completion of Objective 2 will reveal the topology of magnetic field lines between active regions into interplanetary space and the time variation of that connection, identifying whether some active regions connect to a broad range of latitudes and longitudes.

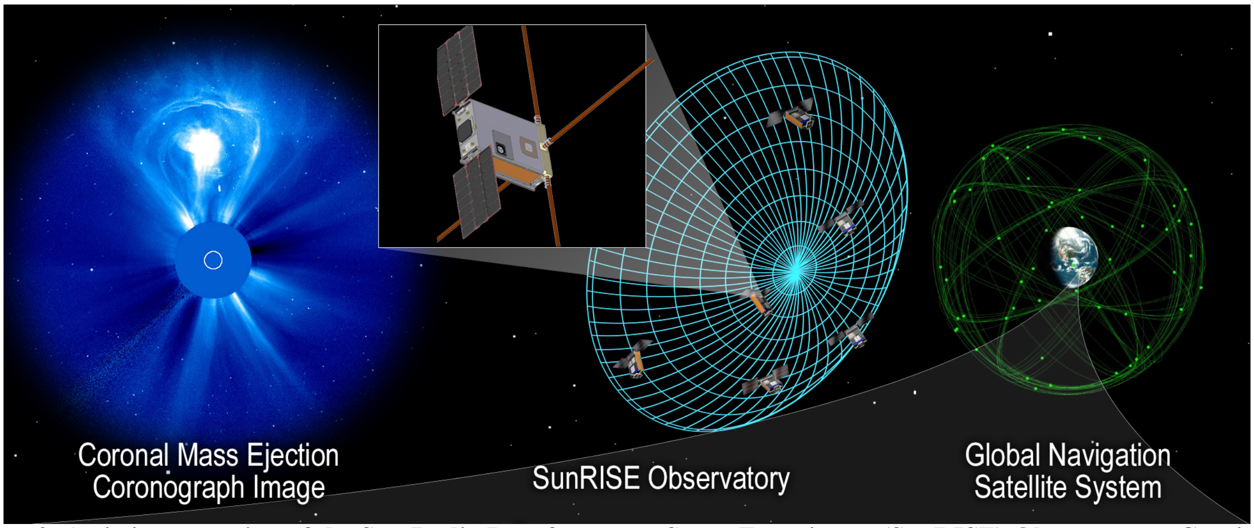

Figure 2. Artist's conception of the Sun Radio Interferometer Space Experiment (SunRISE) Observatory. Consisting of six small space vehicles, each with a 6U form factor, SunRISE will form a synthetic aperture to observe solar radio bursts. Signals from Global Navigation Satellite System (GNSS) satellites will be received simultaneously on the SunRISE space vehicles. Subsequent ground-based processing will use the GNSS signals to obtain precise orbit determination of the SunRISE space vehicles, providing the required knowledge to form the synthetic aperture, also obtained via ground-based post-processing.

3. Mission Architecture

The SunRISE mission will form a synthetic aperture or radio interferometer in order to localize the radio emission associated with particle acceleration and transport in the inner heliosphere. The technique of aperture synthesis or interferometry is well established (e.g., Taylor et al. [28]; Thompson et al. [29]), with Sir Martin Ryle having been awarded a portion of the 1974 Nobel Prize in Physics for his work in developing it. For decades, ground-based interferometers have been used to study solar radio emission (e.g., Gopalswamy & Kundu [10]; Bowman et al. [3]; Raja et al. [25]; Morosan et al. [21]; Zucca et al. [34]), though these observations have been limited to low altitudes (typically < 3 R_S) because the Earth's ionosphere typically limits observations to frequencies above about 20 MHz, and an *ad hoc* interferometer has been constructed from the Cluster spacecraft to localize auroral kilometric radiation (AKR, Mutel et al. [22,23]). An aperture synthesis technique was adopted to obtain the required localization performance because a single monolithic aperture would have unreasonable dimensions (> 6.5 km).

The architecture of the SunRISE mission is distinct from the standard model for NASA missions. The SunRISE Interferometer is composed of a space-based Observatory and a ground-based Science Data System (Figures 2 and 3). In turn, the Observatory is composed of six space vehicles, with each space vehicle composed of a payload and a spacecraft. The Observatory will fly slightly higher than geosynchronous orbit (GEO), well above Earth's ionosphere and plasmasphere. Such an orbit allows frequencies to be received across the entire relevant range without risk of absorption from either the ionosphere or plasmasphere. Rather than a single spacecraft carrying multiple instruments, the SunRISE mission is effectively a single "instrument" constructed from multiple, identical Space Vehicles.

The Observatory's six independent and identical space vehicles record solar DH and global navigation satellite system (GNSS) signals and later transmit those data to the ground. GNSS precise orbit determination (POD) solutions are used to determine the relative propagation delays between each pair of space vehicles and cross-multiply the radio signals coherently in the Science Data System, thereby forming a synthetic aperture with the required localization capability. The multiple space vehicles in the Observatory provide redundancy and graceful degradation.

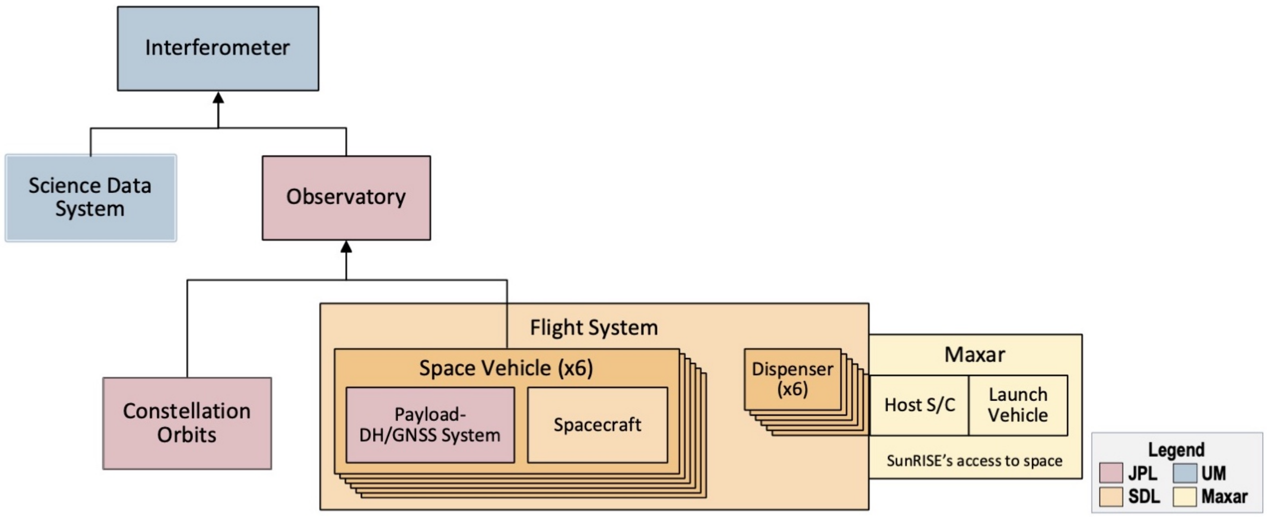

Figure 3. The SunRISE mission architecture is designed to form a single Interferometer, with which measurements will be made to track particle acceleration and transport. The Interferometer (or "instrument") is composed of a (ground-based) Science Data System and (space-based) Observatory. In turn, the Observatory is composed of six (identical) Space Vehicles, with each Space Vehicle composed of a Payload and a Spacecraft. The color of a box indicates the mission partner responsible for that element of the mission, as specified in the legend to the right.

The SunRISE mission has three enabling features:

Knowledge, not Control

As is standard for all interferometers, the antenna positions do not need to be controlled so long as they are known to sufficient accuracy. This knowledge is obtained during post-processing, making use of GNSS signals received by the integrated Solar DH-GNSS receiver.

Integrated Solar DH-GNSS Receiver

The Solar DH signal chain of the SunRISE payload will measure the electric fields from solar radio bursts, while the GNSS signal chain will record simultaneously signals from GNSS satellites in view. The GNSS signals will be used in subsequent ground-based POD to provide the space vehicle location and time used for the interferometry.

FX Correlator for Interferometry

The estimation of the spatial coherence function, or correlation, will employ an approach in which the first step is to transform the received Solar DH signals to the spectral domain (`F` step). The cross-multiplication of the Solar DH signals between space vehicles (`X` step) will be conducted on the ground in the Science Data System. The Science Data System also handles subsequent imaging and localization of the solar radio burst. Consequently, there is neither a requirement nor capability for communication between the space vehicles, and they will operate independently.

These mission-enabling features enable SunRISE to be the first dedicated space-based radio interferometer.

4. Mission Elements

We describe the mission elements in ascending order (viz. **Figure 3**).

Solar DH-GNSS Payload

Figure 4 shows the high-level architecture of the SunRISE Solar DH-GNSS Payload, which integrates Solar DH data acquisition and GNSS signal tracking and provides simultaneous observations of both signal types in a compact unit. The Solar DH signal chain is based on a previous JPL payload, covering a similar but narrower frequency range, that was developed for the DHFR mission. The GNSS signal chain has heritage from JPL's Cion GNSS receiver. The payload also carries a reference oscillator from which down converters and samplers are run commensurably for both GNSS and Solar DH signal chains, ensuring that the times of the Solar DH data acquisition can be determined relative to GNSS time and allowing use of GNSS-determined precise orbit determination solutions in forming higher-level Solar DH data products (most notably, the SunRISE interferometric visibilities).

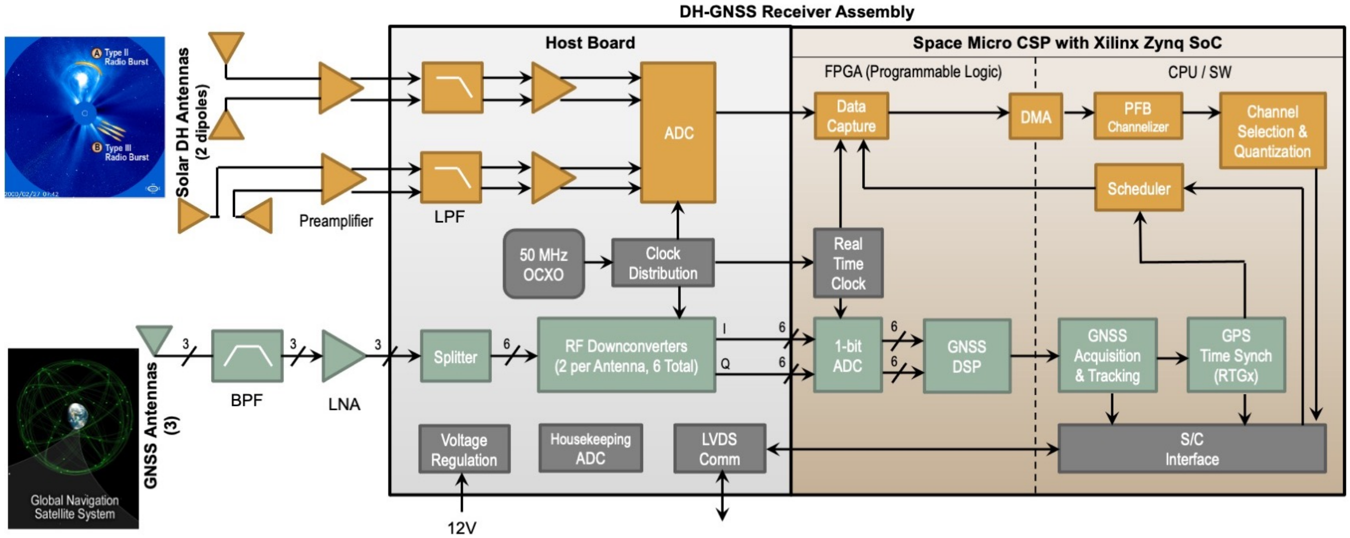

Figure 4. High-level SunRISE Solar DH-GNSS Payload architecture. Integrating a signal chain for receiving decametric-hectometric (DH) solar radio bursts (Solar DH data acquisition, *top* signal path) and a signal chain for receiving Global Navigation Satellite Systems (GNSS) signals (*bottom* signal path), the Solar DH-GNSS payload leverages considerable JPL instrument experience for high frequency (HF band) and GNSS signal reception to produce a compact unit. Sharing a common clock (OCXO), the Solar DH-GNSS payload ensures subsequent knowledge of when Solar DH data were acquired and the space vehicle orbits, both determined by ground-based processing.

The Solar DH signal chain, consists of the following elements.

Electrically short, dual-polarization dipoles, with each dipole constructed from two deployable STACER elements, will receive the incident radiation. Each STACER element, upon deployment, will be 2.5 m in length, forming a dipole that is 5 m long (tip-to-tip). There have been over 650 successful STACER deployments of a variety of lengths and diameters, including for the STEREO/SWAVES instrument (Bale et al. [1]). The STACERs are mounted on the side of the spacecraft that normally faces away from the Sun during flight ($-z$ direction). Once the space vehicles are in their notional orbits for science data acquisition, the STACERs are commanded to deploy.

Preamplifiers, one for each dipole, with a high input impedance ensure impedance matching to the rest of the signal chain. The presence of these preamplifiers is required in order to maintain nearly Galactic-background limited sensitivity over most of the SunRISE required frequency range.

Discrete **low-pass filters** (LPFs) ensure that frequencies above the SunRISE operational frequency range, for example, from FM radio transmitters, are not present in subsequent digitization and signal processing. Additional amplification ensures that the signal voltage levels are at the required levels for digitization.

Dual-channel **analog-to-digital converter (ADC)** digitizes the signals for subsequent on-board processing. A bit depth of 16 bits has been determined to be sufficient to ensure robustness against both in-band and out-of-band (terrestrial) transmitters.

Polyphase filter bank (PFB), leveraging a CASPER design (Parsons et al. [24]), will generate spectral data, thereby performing on-board `F`-engine processing for SunRISE's FX architecture correlator.

Over the 0.1 MHz to 23 MHz SunRISE frequency range, a total of 4096 frequency sub-bands are generated. A programmable subset of these frequency sub-bands will be selected from each spectrum and recorded for future downlink. The Solar DH software will support a programmable rotation scheme, in which a set of 64 frequency sub-bands are selected every 100 ms, which then are passed to the spacecraft for future transmission to the ground. In principle, this sub-band rotation scheme allows each sub-band in the full 4096–sub-band spectrum to be downlinked once every 6.4 s. In practice, it is expected that some frequencies will contain enough interference that they will rarely, if ever, be selected for subsequent downlink. The programmable nature of this frequency sub-band rotation allows different frequencies to be selected, such as might be necessary if there are different terrestrial transmitters (interferers) at different locations on the Earth. This frequency sub-band rotation approach is both consistent with past practice (e.g., WAVES instrument, Bougeret et al. [2]) and reduces the data downlink requirements.

Simultaneously with the Solar DH data, the Solar DH-GNSS payload will collect Global Navigation Satellite System (GNSS) signals. The collection of GNSS signals will enable subsequent ground-based precise orbit determination, which will be used to ensure that the space vehicles are in the desired orbits and for construction of higher-level SunRISE data products (during the `X`-engine portion of the SunRISE

FX correlator), and the ground-based determination of the times of Solar DH data acquisition.

The GNSS signal chain inherits major functions from the TriG receiver (Meehan [20]) and the Cion GNSS receiver for small spacecaraft. Cion receivers are part of the instrument package for the Community Initiative for Continuing Earth Radio Occultation (CICERO). Commercially available GNSS antennas mounted around the body of the spacecraft will enable visibility of GNSS satellites throughout the SunRISE orbit. The received GNSS signals will be filtered, amplified in order to enable weak signal acquisition, and converted to baseband. The analog front-end output will be sampled and digitally processed by the commercially-available Zynq 7020 processor using the CICERO Cion sampler design.

All on-board processing, most notably the polyphase filter bank to obtain the `F`-engine and the GNSS signal acquisition and tracking, will be conducted with a commercially-available Space Micro Cubesat Processor (CSP).

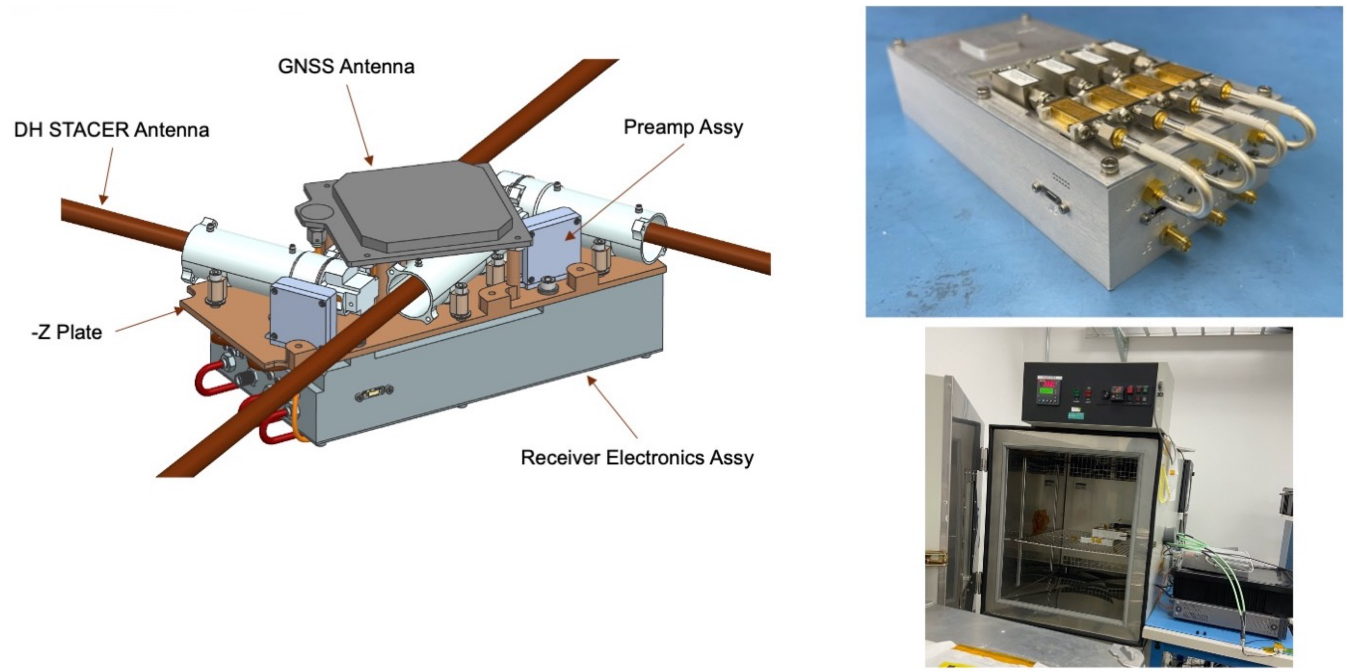

Figure 5. (*left*) Computer-aided drawing showing the major sub-systems of the Solar DH-GNSS Payload. The −Z Plate normally will face opposite the Sun during flight and, together with the spacecraft chassis, forms an integrated Faraday cage to minimize interference from the spacecraft electronics. (*top right*) Engineering model of the Receiver Electronics Assembly. In this orientation, the −Z Plate is at the bottom of the unit. (*bottom right*) Engineering model prepared to undergo thermal testing.

During Phase B, a detailed design of the Solar DH-GNSS payload was developed (Figure 5 and 5), and an engineering model constructed, which has begun to undergo tests required prior to flight (Figures 5 and 6). The Solar DH-GNSS payload remains within its allocations (power, mass, volume), the demonstrated Solar DH signal chain performance remains consistent with that from previous missions (notably Wind/WAVES and STEREO/SWAVES), and, at the time of writing, the phasing between the Solar DH and GNSS signals is being tested to ensure that it remains sufficiently well aligned to enable the ground-based processing to construct the interferometer.

During the course of the design and testing, several changes or modifications were required. Examination of Figure 5 shows several regions where an effective capacitor could be produced, and "stray capacitance" could result. Considerable effort has been devoted to ensuring that this "stray capacitance" would not be so large as to affect the overall Solar DH signal chain sensitivity. An example of another change is that original SunRISE design had four GNSS antennas, one mounted on the side of the spacecraft that normally will face the Sun in flight. (This GNSS antenna is the dark gray square between the deployed solar panels in Figure 2.) It was realized that this face of the spacecraft almost never is oriented toward GNSS constellations and that this GNSS antenna provided essentially no value for the GNSS processing. This GNSS antenna was removed, resulting in a reduction of the payload's mass.

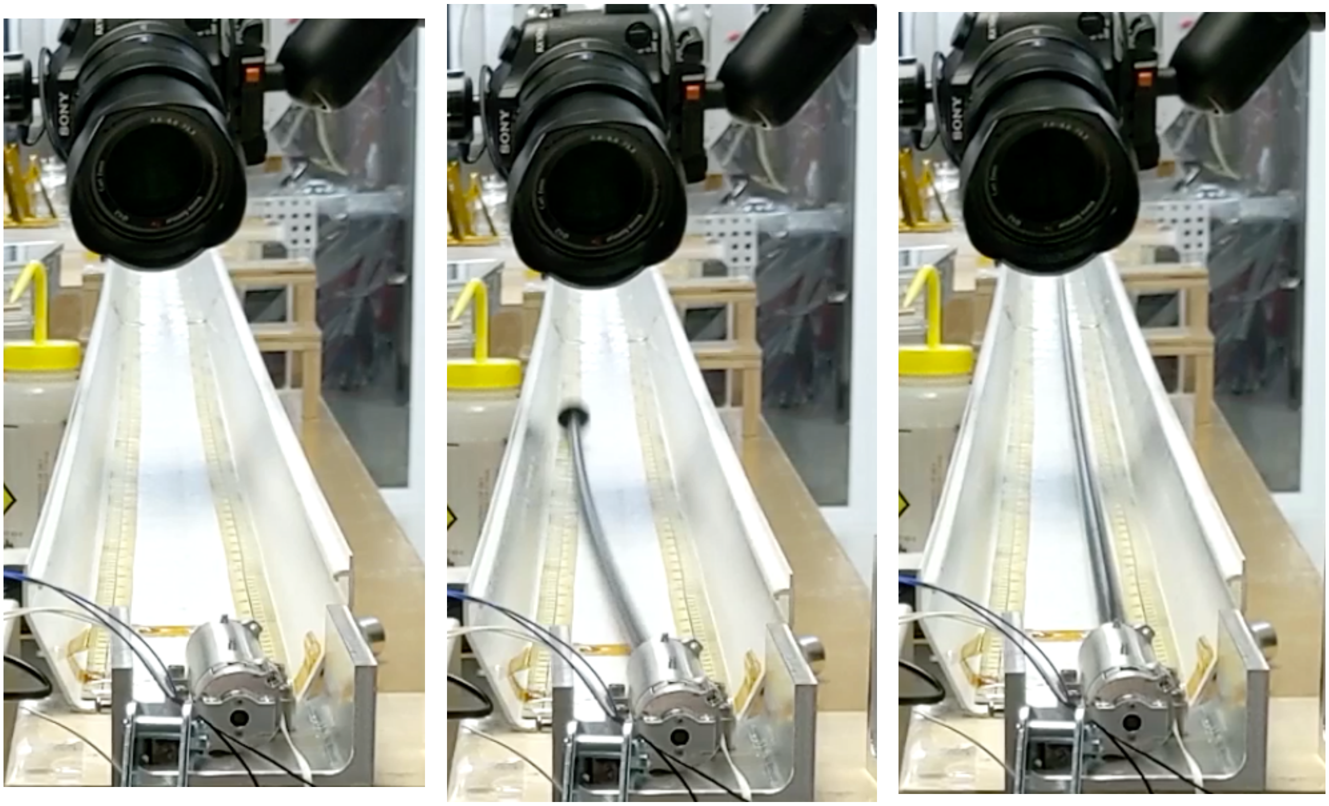

Figure 6. Testing of one of the deployable elements that will form the SunRISE Solar decametric-hectometric (DH) antennas. Each Solar DH antenna will be a 5 m dipole formed by two, 2.5 m long deployable elements, known as STACERs. Packaged into the gray canister at the bottom of each picture is a spring-loaded telescoping antenna. Upon a deployment command, a restraining mechanism is cut loose, and the deployable element extends to its full length. This sequence of images shows (*left to right*) the pre-deployment configuration, which will be the configuration during launch and initial constellation formation; during deployment; and post-deployment, which will be the configuration for the science operations. The deployment is less than 1 second in duration.

During Phase B, the SunRISE project has had some challenges associated with obtaining enough components for the payload, notably amplifiers. This challenge is the result of reductions in the global supply chain during the COVID-19 pandemic. Several small design changes occurred between engineering model and the first flight model to accommodate the limited availability of the original amplifier package. The primary change involved a redesign of the layout of the pre-amplifiers and amplifiers on boards. This change is effective for all flight models, and all of them will be subjected to the same testing.

Spacecraft and Space Vehicle

A SunRISE space vehicle is composed of the combination of a 6U spacecraft, produced by the Space Dynamics Laboratory (SDL), and the Solar DH-GNSS payload. Once the Solar DH-GNSS payload is integrated, the space vehicle payload bay forms a Faraday cage, so as to minimize interference from spacecraft sub-systems corrupting the science data measurements.

The 6U spacecraft design follows the form factor defined in the Planetary Systems Corporation Canisterized Satellite Dispenser standard. This design allows for the use of many standard sub-system components, with the result that the SunRISE mission budget is relatively modest while achieving Decadal-level science. This design provides sufficient volume for the Solar DH-GNSS payload (at least 10 cm × 20 cm × 5 cm) and allows the mission to take advantage of the Planetary Systems Corporation Canisterized Satellite Dispenser for a hosted rideshare to orbit.

The major spacecraft sub-systems will be propulsion, avionics, attitude determination and control system (ADCS), telecommunications radio, and electrical power system (**Figure 7** and 8).

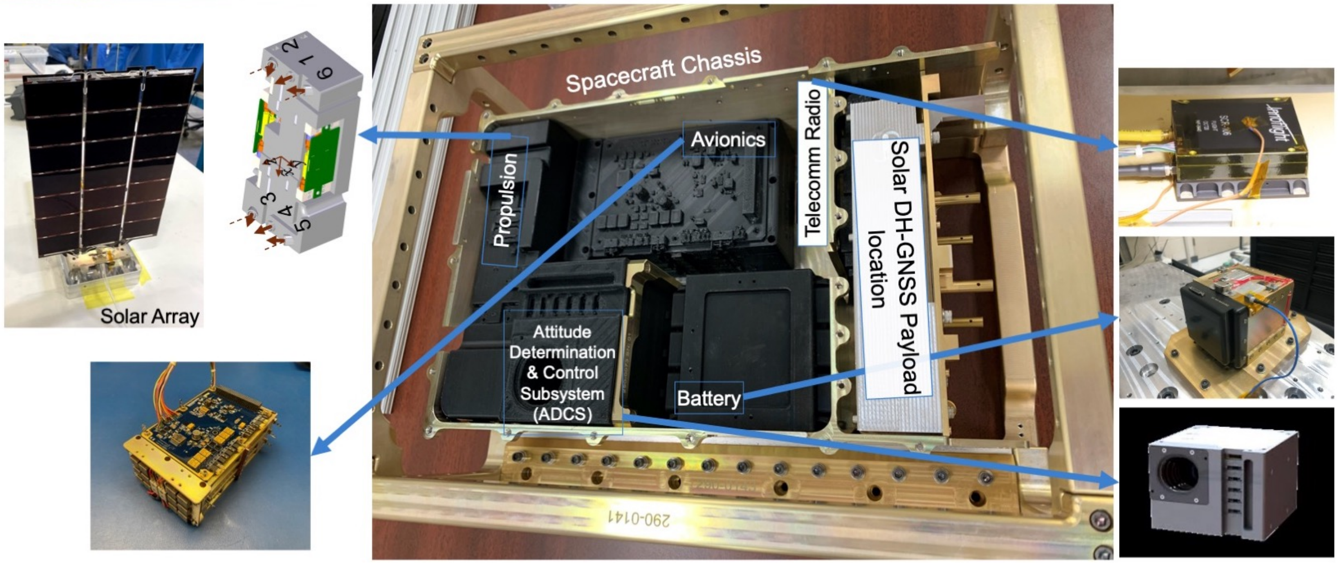

Figure 7. The central portion of the illustration shows an initial SunRISE 6U spacecraft constructed for the purposes of verifying the accommodation of the major sub-systems. The gray and white boxes are additively-manufactured representations of the major sub-systems, with insets showing engineering or test models of several of these sub-systems under test at the Space Dynamics Laboratory (SDL). The solar arrays and the battery together are significant components of the electrical power system. In flight, the left-hand side of the spacecraft in this figure will be the Sun-facing portion, which is also where the solar arrays will be mounted. The Solar DH-GNSS Payload location is indicated, on the right-hand side of the spacecraft in this figure.

Propulsion: A simple cold gas unit, using inert R-234a as a propellant, similar to the design used for the BioSentinel and Lunar Flashlight missions.

Avionics: A combination of SDL's standard single board computer and interface extension card. Both are based on the PCI/104 form factor and connector, with slightly larger boards to accommodate larger, radiation-tolerant parts.

ADCS: The Blue Canyon Technologies (BCT) XACT-50 includes a star tracker, three Sun sensors, inertial measurement unit, a device (IMU), and magnetometer. The reaction wheels will be capable of storing several days of disturbance torques, and reaction wheel desaturations will occur twice a week.

Power: An off-the-shelf solar array, space-rated battery cells, a control board, and a power switching board. The most significant battery pack discharge will happen after the space vehicle is dispensed from the Canisterized Satellite Dispenser; thereafter the state of charge will be maintained well above 50%.

Telecommunications: The Innoflight SCR-106 transceiver provides an X-band transmitter for downlinking science and engineering data and an S-band receiver for receiving commands, packaged as a single unit. Patch antennas are mounted on the spacecraft, with the X-band patch antenna constructed at JPL and the S-band patch antenna provided by SDL. The X-band transmitter is CCSDS compatible, and both commanding and telemetry downlink are through the Deep Space Network.

At the time of writing,[2] the dry mass margin is holding steady at 11% with nearly 90% of the spacecraft's actual components measured. Power generation margin is steady at 20%, and the battery state of charge is not expected to drop below 60% during nominal operations.

Observatory

The passive formation of the SunRISE space vehicles orbits just above GEO, in a supersynchronous orbit, also known as a "graveyard" orbit (Figure 5). Notionally, the Observatory's orbit would be at least 400 km above GEO, but orbits slightly below GEO also are being considered, as they may be easier to access for certain trajectories of the host spacecraft. Whether the Observatory's orbit is a few hundred kilometers above or below GEO has little effect on its operations. The space vehicle orbits have been designed to oscillate around a reference orbit, with all space vehicle orbits having the same period, so as to obtain a radio interferometer with approximately 10 km separations or interferometric baselines, projected into a plane normal to the Sun-SunRISE line. The SunRISE interferometer will obtain an angular resolution of approximately 0.5° at a fiducial frequency of 3 MHz (equivalent to an altitude of approximately 4 R_S using the Leblanc et al. [17] altitude-density-frequency mapping).

[2] Margins are quoted using the NASA definition.

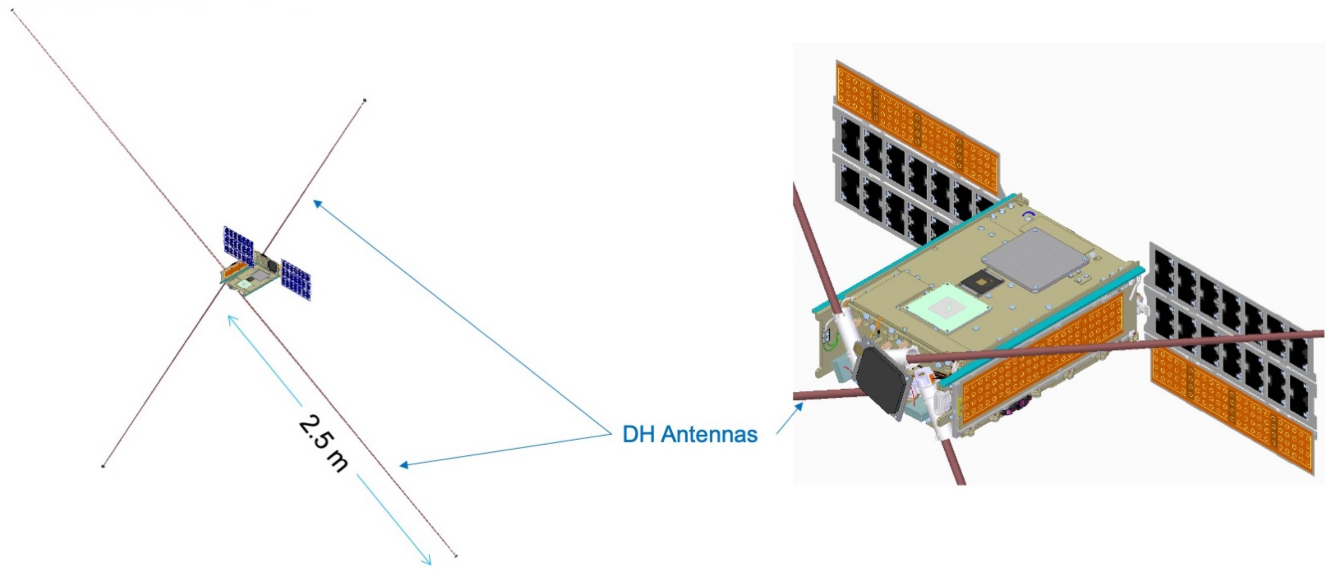

Figure 8. (*left*) Artist's impression of the SunRISE space vehicle, shown to scale. The space vehicle will always be Sun-pointed. The antennas that receive the solar decametric-hectometric (DH) radiation are shown in their deployed state, in which they are 2.5 m long. (*right*) Illustration of a SunRISE space vehicle in flight, with the solar panels oriented toward the Sun (+*z* direction) so as to remain energy-positive and the dipole antennas deployed (on the −Z Plate).

The SunRISE space vehicles are in a dynamically quiet environment, with effects such as the Earth's gravity field, tides, and atmospheric drag having little effect due to the high altitude. Due to the quiet dynamics, the maximum projected velocity change is $\Delta v < 10$ m s^{-1}.

GNSS precise orbit determinations are used, on a weekly basis, to monitor and adjust the orbits, if necessary, to maintain the interferometer. Not only is it required that the orbits remain within an approximate 10 km volume to ensure sufficient angular resolution, the risk of collision between the space vehicles must be kept appropriately small. As an illustration, an uncertainty of only 5 mm s^{-1} in the knowledge of a space vehicle's velocity could result, after one week, in a difference between the expected and actual space vehicle positions of approximately 3 km, which is a significant fraction of the Observatory's diameter. This position uncertainty is not of consequence for the interferometry, as a space vehicle's position at the time of a solar radio burst can be determined in post-processing from the GNSS precise orbit determination. However, if allowed to grow without correction, the risk of collision could exceed acceptable bounds.

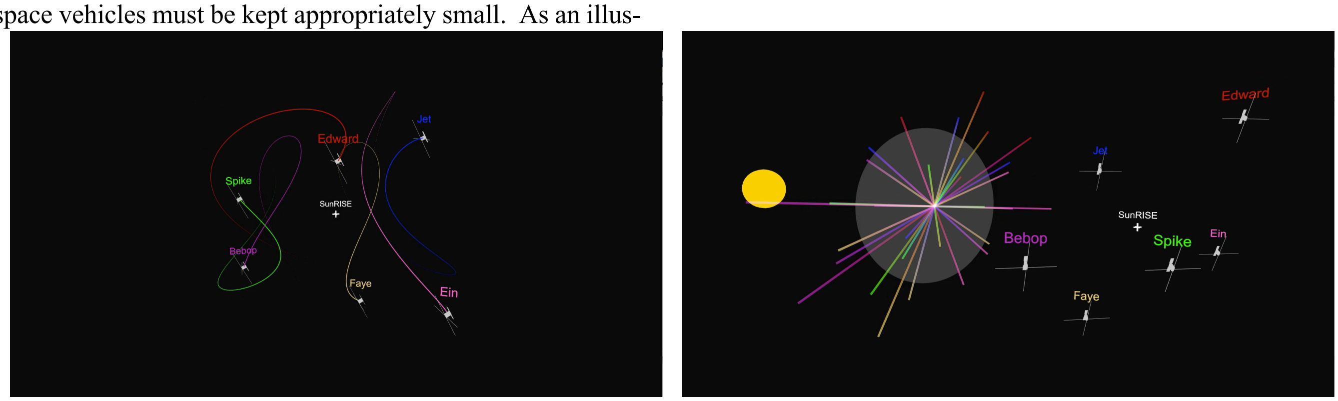

Figure 9. Illustration of the SunRISE Observatory orbits. (*left*) Portion of the individual SunRISE space vehicle orbits, relative to the reference orbit indicated by the SunRISE marker. Each track shows how a space vehicle has moved over a portion of its full orbit. (r*ight*) Formation of the interferometer. The diameter of the disk is 13 km, and the colored lines represent the interferometric baselines, with the color coding designed to show which two space vehicles have contributed to that interferometric baseline.

Ground Data System, Mission Operations System, & Science Data System

The SunRISE Observatory spends most of its time (> 90%) observing the Sun. Once a week, the collected Solar DH and GNSS signals are transmitted, via NASA's Deep Space Network (DSN), to the Mission Operations Center (MOC). The MOC unpacks the DSN telemetry, forming Level 0 data products, and uses the GNSS signals to perform the POD, forming Level 1 data products. These data are transmitted to the Science Operations Center (SOC), which uses the space vehicle positions from the GNSS POD to cross-correlate the Solar DH signals from all unique pairs of space vehicles in order to form the interferometric visibilities (Level 2 data products). Finally, the interferometric visibilities are Fourier inverted to form images, from which the position of the radio emission associated with the Type II or Type III radio bursts are determined (Level 3 data products).

As noted above, the GNSS POD is used for two aspects of the mission—collision avoidance and knowledge of the space vehicle position for the subsequent interferometry. Centimeter-level position determination, or better, in low-Earth orbits (LEO) is common, and, at higher orbits, there is already significant experience. The GIOVE-A satellite carried the Space GNSS Receiver for Geostationary Earth Orbit (SGR-GEO) for the purposes of demonstrating tracking capability of the GPS L1 signal at the altitude of 23,200 km (Unwin et al. [31]); the Geostationary Operational Environmental Satellite-R (GOES-R) weather satellite carries a GPS receiver as its primary means for navigation, tracking both GPS main lobe and sidelobes (Chapel et al. [5]); and the Magnetospheric Multiscale (MMS) mission uses GPS signals for navigation at altitudes as high as 60,000 km to obtain formation flying with separations as small as 10 km (Tooley et al. [30]). This experience, coupled with simulations using JPL's GPS analysis software show that the POD can be obtained at sufficient levels for both predicting collisions and for the sub-meter precision to form the interferometer.

During Phase B, the processing and data storage requirements are being developed and considered for the processing that will occur at the SOC.

5. Mission Operational Stages

The SunRISE mission will have six distinct flight operational stages (Figure 10). Significant effort was invested in Phase B in scoping out these different flight operational stages, in order to understand better the specific activities within each and their timings. Overall, the broad structure and set of activities envisioned previously in Phase A was correct, but Phase B investigations identified several specific activities that needed to be added to various operational stages (Figure 10). As discussed further below, most of these flight operational stages occur during System Assembly, Integration and Test, Launch (Phase D). Because of SunRISE's architecture as a single Interferometer (or "instrument") composed of multiple, identical Space Vehicles, early in the concept development, the Project made the decision to define the boundary between Phase D and Operations and Sustainment (Phase E) as being when the Observatory is fully formed and ready to acquire science data. That is, the Project considers integration to occur partially after launch.

Near the conclusion of Phase D, the Operations Readiness Review (ORR) will be held to ensure that all of the ground operations can support the launch and subsequent flight activities. After this review, the space vehicles will be placed into storage, at which point all the mission systems are "ready for launch." Three to four months before launch, the space vehicles will be removed from storage and shipped to the host satellite provider (see below) for integration with the host satellite and subsequent launch.

Launch and Achieve SunRISE Orbit

The SunRISE space vehicles are designed to fit in a Canisterized Satellite Dispenser, mounted onto a host satellite, e.g., GEO communications satellite. The SunRISE space vehicle dispenser will be mounted in an unused battery compartment of the host satellite. The only interfaces between the SunRISE space vehicles and the host satellite will be an electrical interface to activate the container's deployment switch and a thermal interface by which the host satellite can provide heat to keep the SunRISE space vehicles at room temperature throughout the transfer to GEO. Once the nominal SunRISE orbit is reached, the SunRISE space vehicles will be deployed from the host satellite via real-time ground commands.

SunRISE Space Vehicle Initiation

Following deployment, each SunRISE space vehicle will perform a power-up and checkout sequence, after which the solar arrays will be deployed. There is a short interval during which the ADCS and propulsion sub-systems are inhibited, in order to ensure that the SunRISE space vehicles do not collide inadvertently with the host satellite. Subsequently, the ADCS will arrest any rotation and point the space vehicle towards the Sun. Approximately 40 min. after deployment, NASA's Deep Space Network (DSN) will establish communications with each SunRISE space vehicle in order for the space vehicle to report its status. The DSN also will transmit any updates to the notional space vehicle ephemeris and commands to power-on the Solar DH-GNSS payload. In order to receive status and transmit commands to all six space vehicles, two DSN antennas will be used, with the antennas alternating between the six space vehicles.

Constellation Formation

Following initial post-ejection checkout, each space vehicle will remain in its initial orbit while the payload collects GNSS observables. Once these GNSS data have been collected, the observables will be downlinked via the DSN for ground-based POD processing. The ground operations team will establish the orbital characteristics of each space vehicle, design the maneuvers to target each space vehicle for its desired relative orbit in the Observatory, and sequence the maneuvers. The appropriate commands will be transmitted via the DSN to all six space vehicles, again with two DSN antennas alternating to receive the GNSS observables and transmit the maneuvering sequences. These initial targeting maneuvers will be conducted approximately three days after the initial ejection from the host satellite. This three-day pattern of GNSS tracking, POD, maneuver design, and sequencing will be repeated for an insertion into the targeted orbits.

After this six-day phase, the space vehicles should be in their appropriate relative orbits, and science commissioning phase could begin.

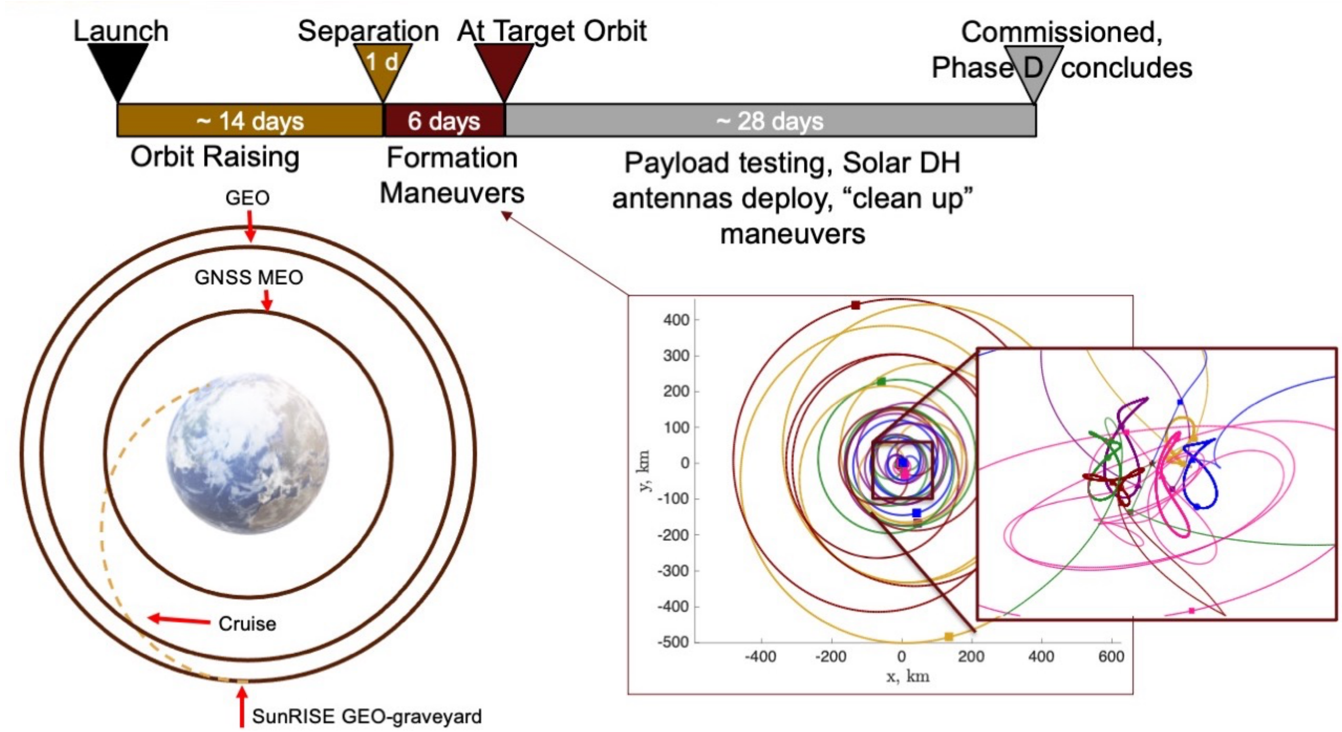

Figure 10. Illustration of major activities between launch and the conclusion of Science Commissioning, which also marks the conclusion of Phase D and the initiation of Phase E (Science Operations).

Science Commissioning

Following constellation formation, science commissioning will begin. This flight operational phase will begin with the space vehicles in their intended orbits, the Solar DN-GNSS payload powered on and operational, but the Solar DH antennas *not* deployed.

Sample Solar DH science data and GNSS observables will be collected and downlinked. A two-fold assessment of these sample science data will be conducted. These sample science data will be the first opportunity to assess the in-flight performance of the Solar DH signal chain of the payload, and therefore the first opportunity to identify any potential discrepancies or anomalies between the pre-launch testing on the ground and the in-flight performance. Second, these sample science data can be used to identify frequencies likely to be entirely useless for subsequent science observations. Even though the Earth's ionosphere provides considerable shielding from terrestrial transmitters over much of the SunRISE frequency band, at the higher frequencies, some transmissions will be detectable. Experience from a variety of ground-based experiments and telescopes shows that the power levels of some transmitters is sufficiently large that they can be received even without the antennas deployed. While the Solar DH signal chain has been designed to be robust against such powerful transmitters, and should not be damaged, at some (small number of) frequencies, it is likely that no useful science data will ever be collected. If there are frequencies that are nearly always contaminated by interference, once those frequencies are determined, there is no reason to downlink those frequencies subsequently.

The GNSS observables will be used for POD processing to confirm that all of the space vehicles are in their intended orbits. The POD processing results will be used to confirm the performance of the ADCS units. If needed, the navigation team will design "clean up" maneuvers to handle any remaining (presumably small) residuals between the intended and actual space vehicle orbits.

After this initial assessment of Solar DH-GNSS payload performance, interference determination, and POD processing, a set of sequences is designed for any updates to sub-system performances, "clean up" navigation maneuvers, and the commands to deploy the Solar DH antennas. Two DSN antennas will alternate in transmitting these sequences of commands to the six space vehicles.

Two cycles of payload data acquisition and ground processing then will initiate. Each cycle consists of collecting Solar DH data and GNSS observables on each space vehicle, downlinking those data and observables to the ground, and processing and analysis. With the Solar DH antennas now deployed, the performance of the Solar DH signal chain again will be assessed and any additional frequencies subject to interference will be identified. Even with the Solar DH antennas deployed, experience from the Wind/WAVES instrument (Kaiser et al. [13]) and analysis conducted during Phase B suggest that most of the SunRISE frequency range will be useful, with little interference from ground-based transmitters. In a similar manner, the GNSS observables will be processed and the POD results will be used to monitor the space vehicles' orbits and design any remaining required "clean up" maneuvers.

Verifying the performance of the full science pipeline with in-flight Solar DH science data also will occur during the latter portions of Science Commissioning. The duration of Science Commissioning contains sufficient margin (> 50%) that any anomalies or discrepancies with the space vehicles or the Solar DH-GNSS payload can be addressed. Depending upon the nature of any anomalies, verification of the full science pipeline can proceed in parallel with addressing any anomalies. For instance, if the performance of one Solar DH-GNSS payload is off-nominal, the engineering team can focus on understanding its performance while the in-flight data from the other five space vehicles is processed through the science pipeline.

The conclusion of Science Commissioning activities concludes Phase D of the SunRISE mission.

Science Operations (Phase E)

Science Operations are expected to commence immediately upon the successful conclusion of Science Commissioning, notionally four weeks after space vehicle deployment. Projections for the event rate of CMEs, based on the observed numbers from Solar Cycle 24 (at a comparable phase), indicate that Science Operations should last 12 months, during which at least a dozen CMEs will be likely observed (with as many as 20 CMEs expected). This number is sufficient to resolve the Objective 1 science goal of whether there is a primary location for particle acceleration as traced by Type II radio bursts. The number of Type III radio bursts during this same interval could exceed 100.

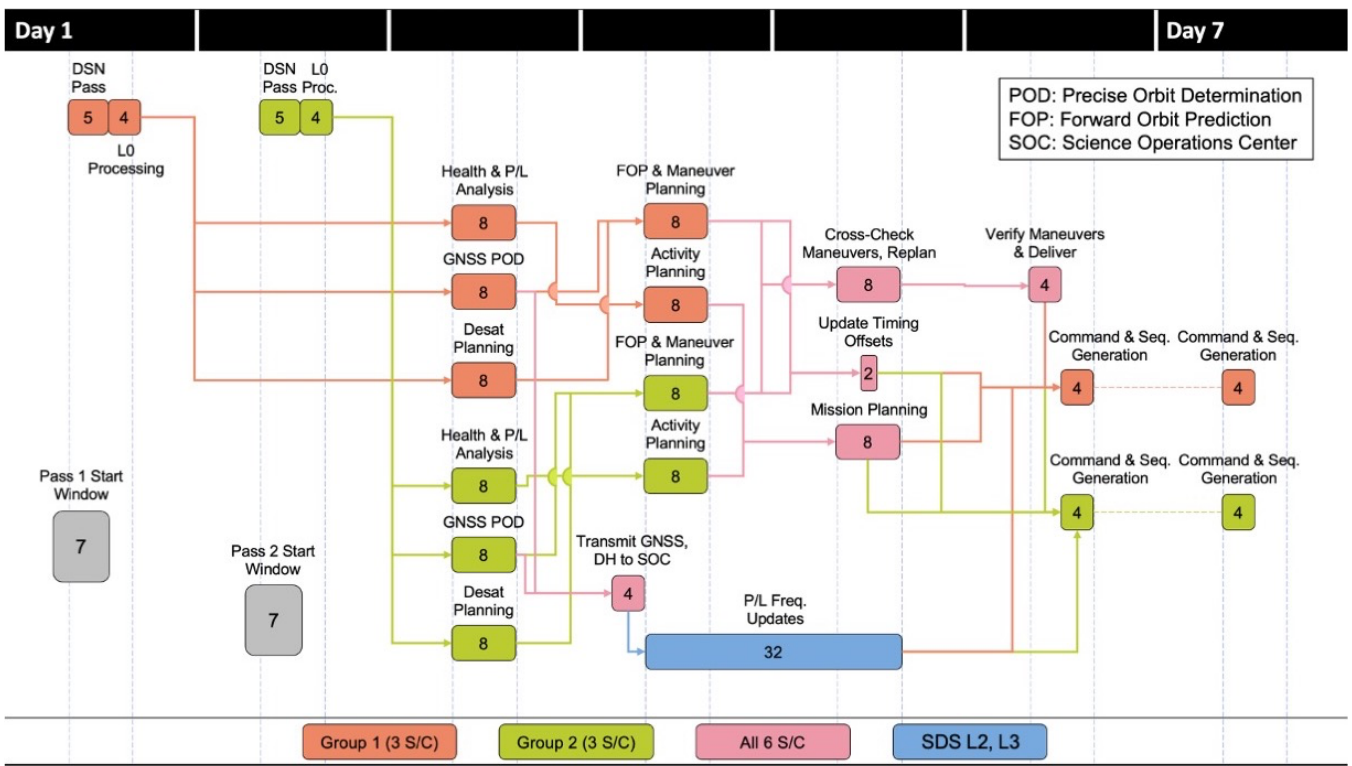

Figure 11. Weekly sequence of ground-based activities, occurring both at the JPL Mission Operations Center (MOC) and the Univ. of Michigan Science Operations Center (SOC). The space vehicles are handled initially in two groups, taking advantage of the Deep Space Network's multiple spacecraft per aperture (MSPA) to downlink science and engineering data from three space vehicles simultaneously. For science data processing and orbit maintenance (mission design & navigation), however, all six space vehicles are considered as an integrated Observatory.

Science data acquisition and ground-based processing will repeat in a weekly pattern (Figure 11). Each space vehicle will spend most of its orbit with the Solar DH antennas, which are co-boresighted with the solar arrays, oriented in the direction of the Sun. Therefore, all space vehicles should have the same orientation, typically to better than a few degrees. Reaction wheels will be used to provide 3-axis control; these reaction wheels will be desaturated periodically using on-board thrusters; the interruption for reaction wheel desaturation is so short that it will have no effect on science observations. Navigation analyses will be conducted weekly to ensure that the projected orbits will not lead to a significant collision risk; any required orbital trim maneuver sequences will be uploaded to the space vehicles on a weekly basis. Mission design analysis has shown that, even if all six space vehicle trajectories are not corrected during a two-week interval, the collision risk will be minimal.

One telecommunication pass per week will be scheduled with the DSN to downlink the science and engineering data, and to uplink any new parameters and sequences. Each space vehicle is estimated to produce up to 3.5 GB of science and engineering data per week. Downlink will be accomplished efficiently by making use of the DSN's multiple spacecraft per aperture (MSPA) capability, in which up to four spacecraft can downlink data simultaneously by using different frequencies (a.k.a. DSN channels) within the frequency range allocated by the International Telecommunications Union for downlink.[3] For SunRISE, downlinks occur in a 2 × 3-MSPA manner in which three of the six space vehicles will downlink their data simultaneously followed by the remaining three space vehicles downlinking their data simultaneously. Typically, the downlinks will be scheduled on successive days and at times selected to maximize solar panel illumination and link margins.

Each space vehicle will have a unique ID. A single DSN antenna, therefore, will be able to uplink to any or all space vehicle at the same time during a telecommunication pass. Each command will contain a unique space vehicle ID, allowing commands to be sent to a specific space vehicle while sharing the same uplink frequency.

After the data are downlinked, they will be unpacked from the telemetry data structure at the JPL Mission Operations Center (MOC). Solar DN-GNSS payload and spacecraft health will be assessed, and the GNSS observables will be used in POC processing to reconstruct the space vehicle positions and orbits during the science data acquisitions. The science data and POD processing results will be passed to the Univ. of Michigan's Science Operations Center (SOC) for processing by the Science Data System (SDS).

At the SOC, two processing approaches will be used in parallel. First, the power levels of Solar DH science data will be assessed with automated functions. These power levels will be used to identify any new interference (terrestrial transmitters) that might have come into view or any developing anomalies in the Solar DH-GNSS payloads. The Solar DH science data also will be averaged over a set of intervals (up to 60 s), designed to identify when any Type II or Type III radio bursts might be occurring. Notionally, all Solar DH science data are processed through the full science pipeline, producing results up to Level 3 images. If the automatic processing suggests that any Type II or Type III radio bursts are identified from the automatic processing, Level 3 localizations will be produced for those times. Second, observations from the suite of heliophysics observations that have occurred during the past week will be used to assess whether any CMEs have occurred. If any have occurred, the SunRISE science data will be examined to assess whether any Type II radio bursts had occurred in association with any of the CMEs. In the case of any CME-associated Type II radio bursts not identified already through the automatic processing, the science pipeline will be restarted to process those specific data and produce Level 3 images and localizations. This focus on CME-associated Type II radio bursts reflects the difference in expected numbers between Type II and Type III radio bursts summarized above—namely at least an order of magnitude more Type III radio bursts are expected as compared to Type II radio bursts. The expected number of Type III radio bursts is more than sufficient to address Science Objective 2 while addressing Science Objective 1 is more sensitive to the number of CME-associated Type II radio bursts that are identified.

For all CME-associated Type II radio bursts, whether identified automatically or from other observations, their radio locations will be compared to the structures of the CMEs to determine where the energetic particles are being accelerated. For Type III radio bursts, the electron trajectories will be determined, with a focus on whether the beams spread in solar latitude or longitude, indicative of rapid particle diffusion or field line spreading.

On a regular basis, notionally every three months, all SunRISE data products are converted to community-standard formats and copied to NASA's Solar Physics Data Facility (SPDF). This availability will enable other researchers either to reprocess the SunRISE data using other algorithms or explore new (potentially not-yet-recognized) science investigations.

Calibration of the SunRISE interferometer itself will be achieved in the standard manner of observing (compact) reference sources. This calibration will verify the accuracies of the relative space vehicle positions as determined from the GNSS POD processing—incorrect space vehicle positions result in phase errors in the visibility data, which then manifest as the images of the reference sources having distorted or extended structures. The extent to which they do not appear unresolved will be used to correct for POD errors (Fomalont & Perley [8]; Thompson et al. [29]).

Two different reference sources have been identified. Jupiter's DH radiation occurs throughout the SunRISE frequency range, and the emitting regions are sufficiently small that they should appear point-like and unresolved to SunRISE

[3] The frequencies used by the SunRISE space vehicles are within the "near Earth" band (8450 MHz–8500 MHz), for spacecraft within two million kilometers of Earth.

(Carr et al. [4]). Second, a number of ground-based ionosondes transmit across at least a portion of the SunRISE frequency range. With a distinctive sweep in frequency, and occurring at regular intervals, they also can serve as reference sources. While their signals likely will suffer complete ionospheric absorption when SunRISE Observatory is over the daytime hemisphere, the higher ionosonde frequencies likely break through when SunRISE is over the nighttime hemisphere.

Finally, while not required for the SunRISE mission, it is likely that a new DSN capability will be tested during Science Operations. Analogous to the MSPA capability, which enables multiple simultaneous downlinks, the DSN is developing a multiple uplinks per aperture (MUPA) capability, in which commands are sent simultaneously to multiple spacecraft from the same DSN antenna. The intent is that the MUPA capability will provide more efficient uplinks to (small) spacecraft at other locations in the Solar System (e.g., the Moon, Mars). The operational plan is that the DSN will command the SunRISE space vehicles serially, but two tests of the MUPA capabilities are planned currently. Testing with the SunRISE space vehicles would provide an initial verification of the DSN's MUPA capability, though the (low) relative velocities between the SunRISE space vehicles ($\sim$ 1 m s^{-1}) is less than that expected from independent spacecraft orbiting another planetary body (> 1 km s^{-1}).

Decommissioning (Phase F)

SunRISE operates exclusively in the supersynchronous GEO (a.k.a., GEO graveyard), which is already a disposal orbit. At the end of mission, each space vehicle is commanded to alter its orbit slightly to ensure that the space vehicle cannot collide with each other, the power system is disabled, and the system passivated. On the ground, final processing of the engineering telemetry and science data occurs, with all data transmitted to NASA's Solar Physics Data Facility (SPDF).

6. SUMMARY

The SunRISE mission will address key unsolved Decadal-level questions in Heliophysics, but do so with a Mission of Opportunity implementation. The mission will construct a radio interferometer from a passive formation of six 6U space vehicles by leveraging significant recent advances in small spacecraft technologies, ground operations within the Deep Space Network, and standard procedures and techniques from radio astronomy.

The SunRISE Science Objectives are to address fundamental questions in particle acceleration and transport. The SunRISE science investigation will track the positions of two kinds of decametric-hectometric (DH) solar radio bursts to achieve these Science Objectives. (**1**) DH Type II radio bursts are generated by electrons energized near expanding coronal mass ejections (CMEs); by tracking the positions of DH Type II bursts as a function of time (and frequency) relative to CME structures, SunRISE will constrain the locations of electron acceleration regions. (**2**) DH Type III radio bursts are produced by electrons released by solar flares along open field lines; by tracking the positions of DH Type III radio bursts as a function of time (and frequency), SunRISE will constrain how electrons are transported into the heliosphere and constrain how electrons can flood interplanetary spacecraft that are apparently not magnetically connected to an active region.

Each SunRISE space vehicle will carry a science payload that will consist of a dual-polarization dipole and a receiver that integrates the data acquisition of solar decametric-hectrometric (DH) signals and reception of global navigation satellite system (GNSS) signals. Subsequent ground-based processing will use the GNSS signals to determine the precise orbits and times of the space vehicles, allowing correlation of the Solar DH signals to form the interferometer.

Mission operations will be regular and routine. Each week, the space vehicles will be contacted by the Deep Space Network, with science and engineering data downloaded using the DSN's multiple spacecraft per aperture (MSPA) capability. Commands to execute minor orbit trajectory corrections will be uploaded, if needed. On the ground, the GNSS signals will be processed for precise orbit and time determination, after which the signals will be combined to form the interferometer and localize any Type II or Type III radio bursts occurring in the previous week. Ultimately, all data will be transmitted to NASA's Solar Physics Data Facility (SPDF).

While beyond the scope of SunRISE, previous observations of the Universe at radio frequencies below the Earth's ionospheric cutoff have been conducted with only limited angular resolution. SunRISE will provide much higher angular resolution, and other planetary and astronomical sources than just the Sun might ultimately be possible to study.

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BIOGRAPHY

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