NASA INTERFEROMETER TO STUDY THE SUN USING SMALL SATS

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PAPER

The Sun Radio Interferometer Space Experiment (SunRISE) mission uses smallsat technologies to create a space-borne interferometer. The mission will differentiate hypotheses on how magnetic energy in the corona is converted into intense relativistic particle radiation and how this radiation propagates into interplanetary space. SunRISE will localize solar radio emissions using a >10-km wide synthetic aperture consisting of six identical space vehicles.

The Observatory will fly ~300 km above geosynchronous Earth orbit (GEO) in a passive formation. Each space vehicle (SV) is a 6U form-factor spacecraft with a payload comprised of decametric-hectometric (DH, 0.1 MHz–23 MHz) and global navigation satellite system (GNSS) receivers. The DH receiver observes Type II and Type III solar radio bursts. The GNSS receiver provides position and timing information for the DH measurements. SunRISE is unique in that the “instrument” is a combination of the six payloads in space and the ground processing system.

The observing scheme features some key simplifications that enable the SunRISE architecture. SunRISE leverages several state-of-the-art capabilities to accomplish its mission. The SVs are built and in storage awaiting launch.

This paper will describe the SunRISE mission, the architecture and technologies employed, and some of the challenges faced in its development.

1 INTRODUCTION

SunRISE will create a space-based interferometer using smallsat technologies. The mission will differentiate hypotheses on how magnetic energy in the Sun’s corona is converted into intense relativistic particle radiation and how this radiation propagates into interplanetary space. SunRISE uses a >10-km wide synthetic aperture consisting of six identical space vehicles (SVs) to localize solar radio emissions.

The SunRISE flight hardware includes six identical 6U (six-unit) SVs. The SV dimensions are approximately 10 cm x 20 cm x 30 cm and mass is ~12 kg. Each SV is comprised of a spacecraft bus provided by Space Dynamics Laboratory (SDL) and a DH/GNSS receiver payload provided by NASA’s Jet Propulsion Laboratory (JPL).

The six SVs, arranged in a specific orbital arrangement, form the Observatory [7] (Figure 1). When the Observatory is properly tuned by the ground-based Science Data System (SDS), an interferometer (the “instrument”) is formed. Mission operations and Navigation are provided by JPL. Science operations are provided by the University of Michigan (UM). SunRISE uses NASA's Deep Space Network (DSN) for communication.

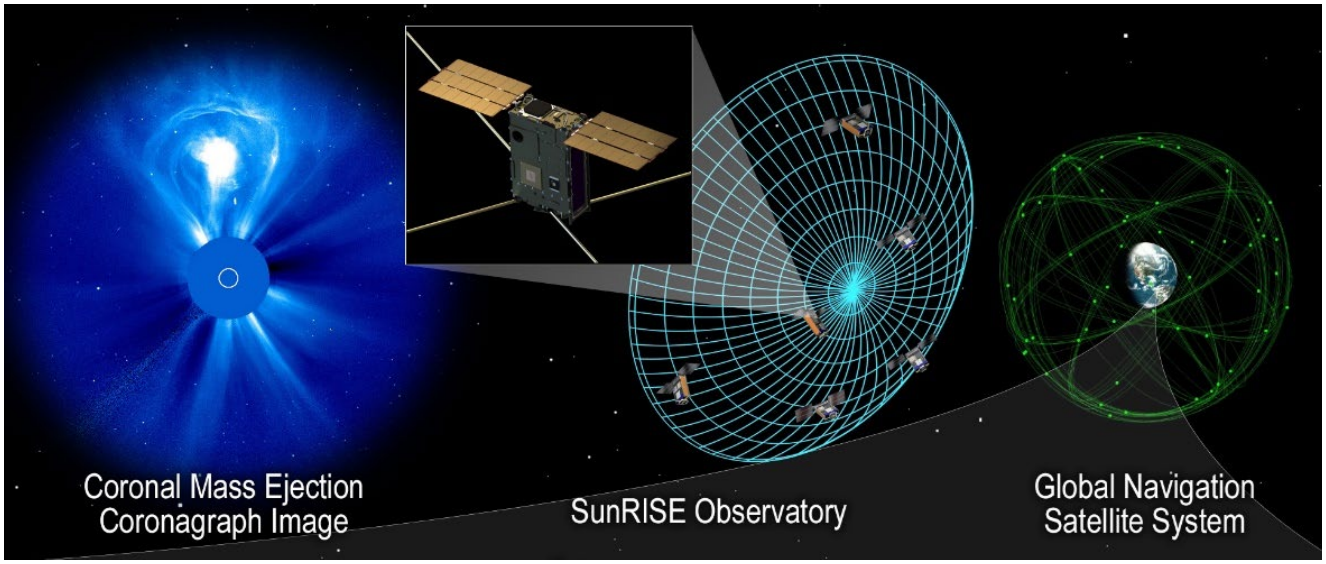

Figure 1. Artist's concept of the Observatory, using six space vehicles to form a synthetic aperture. Signals from GNSS satellites are used for time and position knowledge, which are used by ground-based processing to obtain precise orbit determination (POD) of the space vehicles. POD information for each SV is required for the Science Data System to form the synthetic aperture.

The Observatory of six SVs will fly ~ 300 km above geosynchronous Earth orbit (GEO) in a passive formation, designed to maintain minimum and maximum separations between SVs. Each space vehicle carries a payload comprised of DH and GNSS receivers. The DH receiver is used to observe Type II and Type III solar radio bursts. The GNSS receiver provides the precise position and timing information for the DH measurements needed to form interferometric visibilities and images in ground processing. Surprisingly, a 6U form-factor spacecraft is adequate to support each payload and achieve the mission's objectives.

The standard space mission has been a spacecraft carrying one or more instruments. SunRISE is paradigm shift whereby the instrument is a combination of the six payloads in space and the ground processing system.

This paper will describe the SunRISE mission, the architecture and technologies employed, and some of the challenges faced in its development.

2 SCIENCE MISSION

The SunRISE studies particle acceleration and transport in the inner part of the Solar System or in the inner heliosphere. SunRISE investigates decametric-hectometric (DH) solar radio bursts produced by electrons energized near expanding coronal-mass ejections (CMEs, Type II bursts, [1]) and by electrons released by solar flares along open field lines (Type III, [2]; [3]) (see Figure 2). SunRISE achieves its science objectives by using a space-based interferometer to track these Type II and III radio bursts from 2 solar radii (R_S) to > 20 R_S. SunRISE will measure the location and distribution of Type II radio emissions relative to expanding CMEs, and image the field lines traced by Type III radio bursts from active regions through the corona. To image these solar emissions, SunRISE will collect multiple measurements, distributed across > 10 km, with precise position and time stamps to reconstruct the incident wave fronts.

Since DH wavebands are attenuated heavily by Earth's ionosphere, high-altitude space-based measurements are required, so the SunRISE Observatory will be based at GEO + 300 km, well above Earth's ionosphere and plasmasphere.

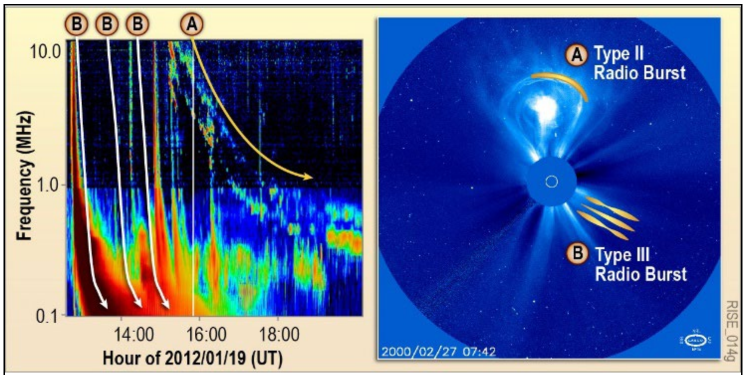

Figure 2. SunRISE uses Type II (A) and Type III (B) decametric-hectometric radio bursts to track particle transport and acceleration within the inner heliosphere. (left) A radio power spectrum from the WAVES instrument on the Wind spacecraft illustrates a storm of Type III bursts preceding a several 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.

Type II solar radio bursts are much less frequent than Type III bursts. Type II bursts are expected at a rate of approximately 15 per year or one or a few per month. By contrast, the rate of Type III bursts can average about 1,000 per month [8]. Both Type II and III bursts are stochastic phenomena, with only broad trends able to be predicted (e.g., more radio bursts occur near the peak of a Solar Cycle, also known as "solar maximum"). Because Type II bursts are less frequent, the Level 1 Science requirement to observe a sufficient number of them drives the lower-level requirements. The probability that SunRISE observes a sufficient number of Type II radio bursts depends on the duration of mission operations, the time the Observatory is able to collect data, the Type II event rate, and the sensitivity of the DH payloads.

For more details about the science objectives, consult papers [4], [5], [6].

3 MISSION ARCHITECTURE

A synthetic aperture was chosen to obtain the required localization performance because the size of a single monolithic aperture (> 6.5 km) would be infeasible. The orbit of GEO + 300 km was chosen because it is well above Earth's ionosphere and plasmasphere and allows frequencies to be received across the entire relevant range without risk of absorption. The orbit is a graveyard orbit, so no additional fuel needs to be carried for end-of-life maneuvers.

The Observatory's six independent and identical space vehicles (SVs) store their solar

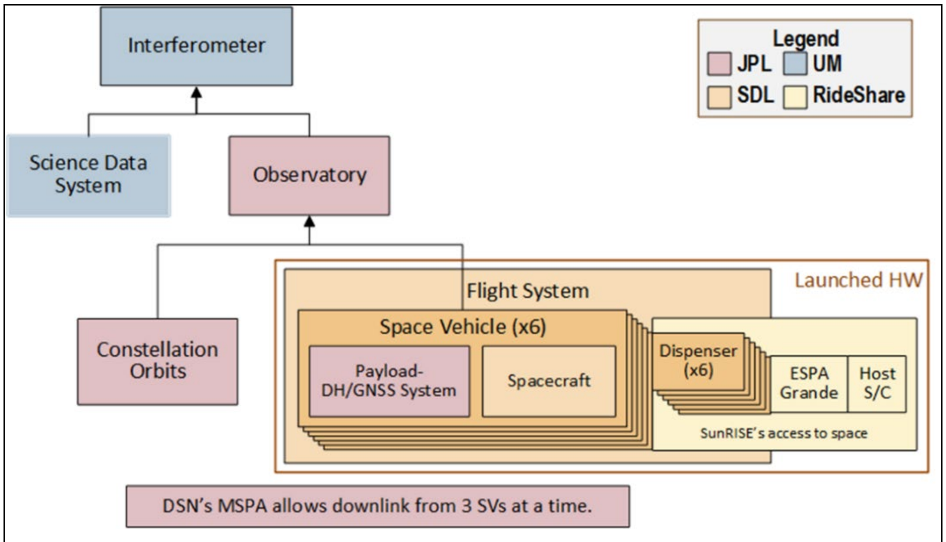

Figure 3. The SunRISE mission architecture forms a single Interferometer, which is composed of a ground-based Science Data System and a space-based Observatory. The Observatory is composed of six identical Space Vehicles flying in a constellation. Each SV is composed of a Payload and a Spacecraft.

DH and GNSS signals and transmit those data to the ground weekly. 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 (SDS), thereby forming a synthetic aperture with the required localization capability. Multiple space vehicles in the Observatory provide redundancy and graceful degradation, with a minimum of five needed for baseline science and four needed for threshold science.

SunRISE takes advantage of the multiple spacecraft per aperture (MSPA) capability of NASA's Deep Space Network (DSN) to downlink large data volumes from three space vehicles at a time using a single DSN aperture, which limits DSN contact to twice per week and minimizes the operations workforce needed.

The space vehicles will be carried to their target orbit as a secondary payload on a Space Force launch, which provides SunRISE affordable access to space. The Space Vehicles are built and in storage awaiting launch, which is expected in the second half of 2025.

The observing scheme features some key simplifications that enable the SunRISE architecture, such as:

- Only position and time knowledge of each space vehicle are required. Active control of a space vehicle trajectory is not needed.
- All vehicles are identical and operate completely independently. All coordination is handled on the ground, which minimizes on-board processing needs.

SunRISE leverages several state-of-the-art capabilities to accomplish its mission:

- The computational horsepower of a CubeSat-compatible, single board computer enables the GNSS and DH receivers to be combined.
- Small packaging of extendable, rigid 2.75-m booms, which form the DH dipole antennas, with simple and reliable deployment mechanisms.
- Existing CubeSat attitude determination and control systems control the space vehicle before and after deployment of the large DH antennas.
- Integrated, 3D-printed, CubeSat propulsion system is used for initial orbit setup, wheel desaturation and orbital maintenance.
- Connections to GNSS from just above GEO provides the required position and time knowledge.

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

4 MISSION ELEMENTS

4.1 Payload

The payload includes one GNSS antenna on each of three sides of the SV; these allow the SV to remain in contact with the GNSS satellites regardless of its orientation. It also includes two 5.5-m dipole antennas for collecting DH data. Each dipole is formed by two 2.75-m deployable STACERs. Each STACER antenna mast is a DAG213-coated Be-Cu STACER spring, extending from an aluminum housing, mounted to the -Z plate of the SV. Figure 4 and Figure 5 show some details of the payload and the STACERs.

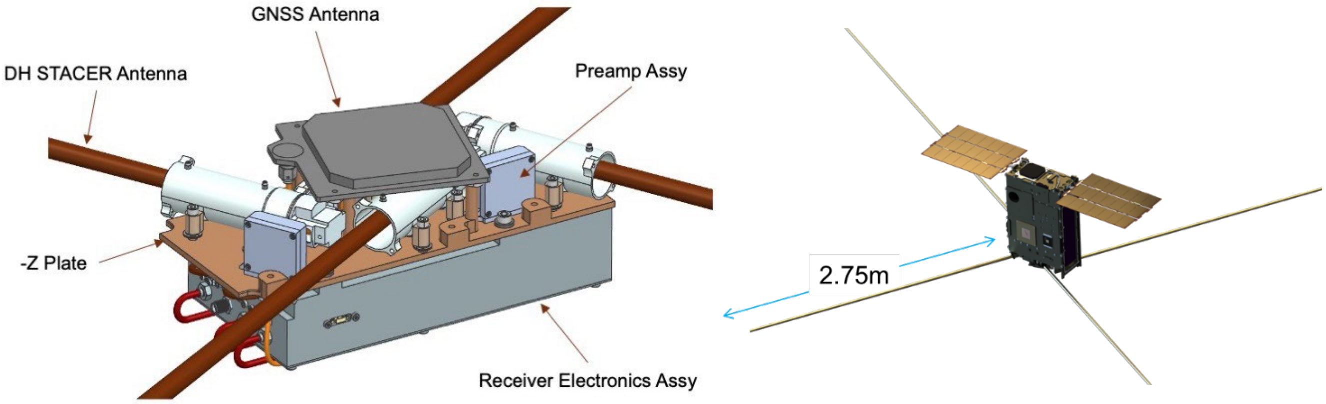

Figure 4. The Payload assemblies are shown on the right. The Space Vehicle is shown on the right. Four STACERs are used for the DH antennas (not shown in their entirety), which form two 5.5 m dipoles. The STACERs are stowed into their cans (93 mm x 32 mm) on the -Z plate for launch and are released by frangibolts soon after the SV is released from the host spacecraft.

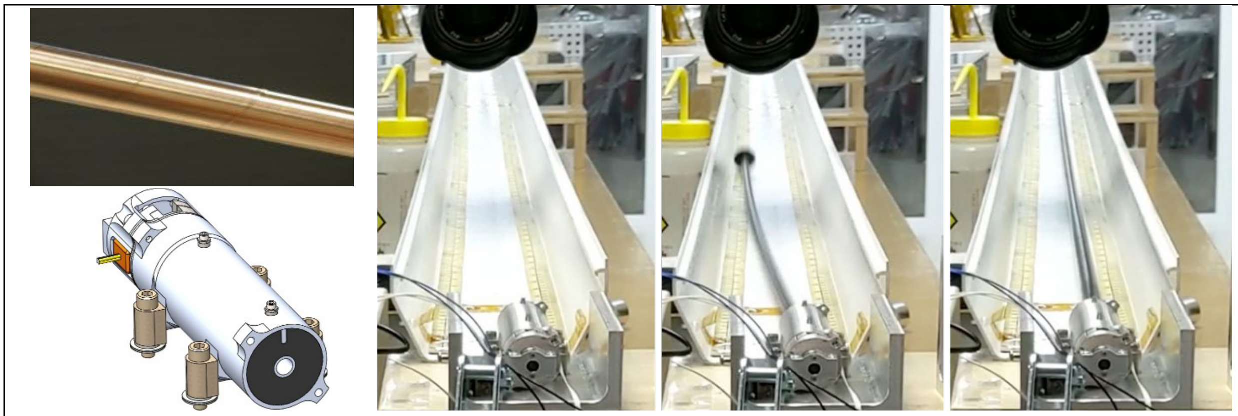

Figure 5. An extended STACER is one half of a DH antenna dipole. A STACER is a spring-loaded, telescoping antenna. At launch each antenna is stowed in its ~93 mm x ~32 mm can (lower left) on the -Z plate of the SV. The mast is DAG213-coated Be-Cu (an uncoated Be-Cu STACER is shown in the upper left). The STACERs extend to ~2.75 m in < 1 second. The three images on the right show a sequence of images of an engineering model in test.

4.1.1 Integrated Solar DH-GNSS Receiver

The payload consists of a dual Decametric-Hectometric (DH) and Global Navigation Satellite System (GNSS) receiver. The DH observing band is 0.1 to 22.6 MHz. DH and GNSS data are paired and processed on the ground to produce final science observations.

The Solar DH signal chain of the SunRISE payload measures the electric fields from solar radio bursts, while the GNSS signal chain simultaneously records 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.

Figure 6 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. 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).

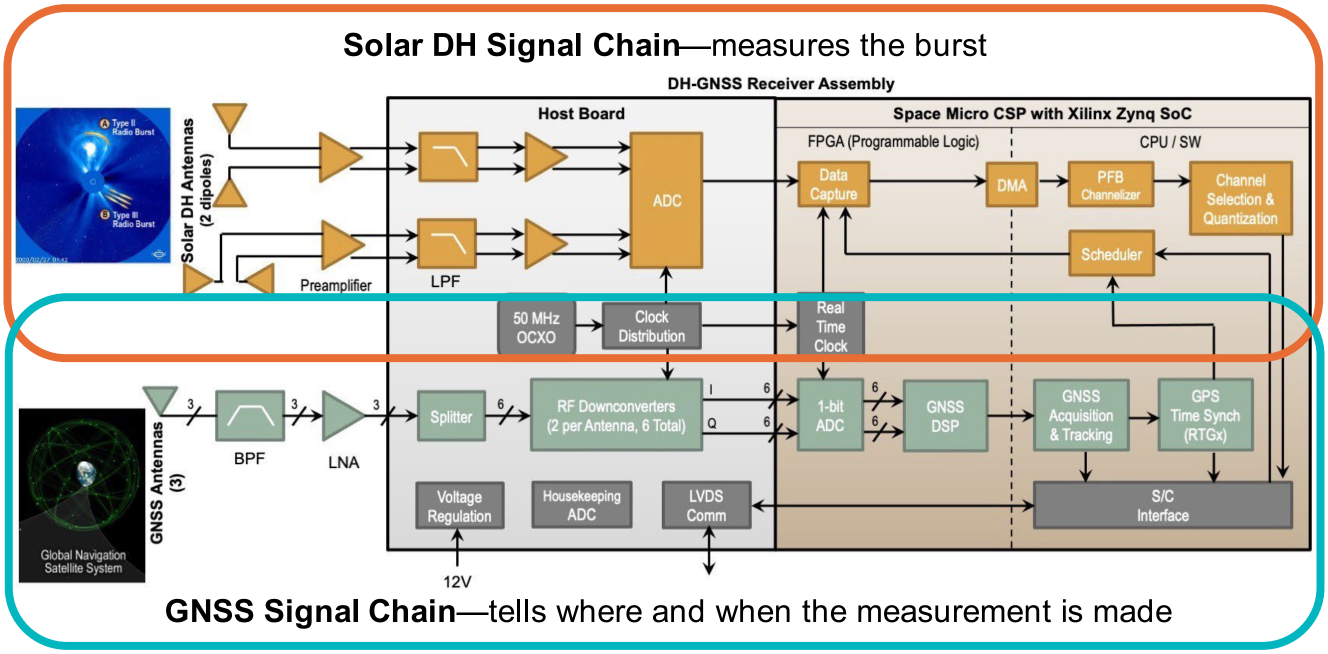

Figure 6. The Payload's electronics are packaged in a compact unit. They integrate a signal chain for receiving DH solar radio bursts (top signal path) and a signal chain for receiving GNSS signals (bottom signal path). The overlap in rounded boxes denotes the shared common clock (OCXO), used to ensure knowledge of when and where DH data were acquired for ground-based processing.

4.2 Spacecraft and Space Vehicle

Space Dynamics Lab (SDL) in Logan, Utah, USA built the Spacecraft and performed integration and test on all six Space Vehicles. Most components are commercial-off-the-shelf and standard components SDL commonly uses when they build spacecraft. Figure 7 and Figure 8 identify the layout of components in and on the chassis. The payload bay in the chassis forms a Faraday cage, to minimize interference from spacecraft sub-systems on the science data measurements.

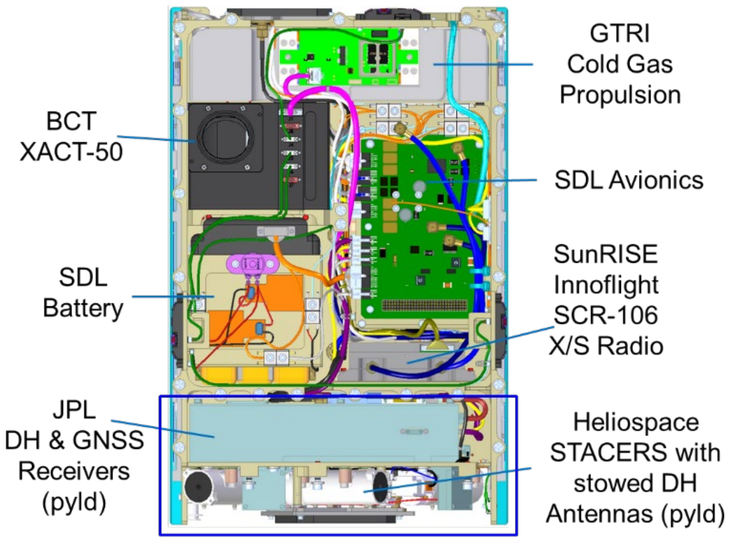

Figure 7. An internal view of the SV shows a very crowded bus. The Payload is outlined in blue.

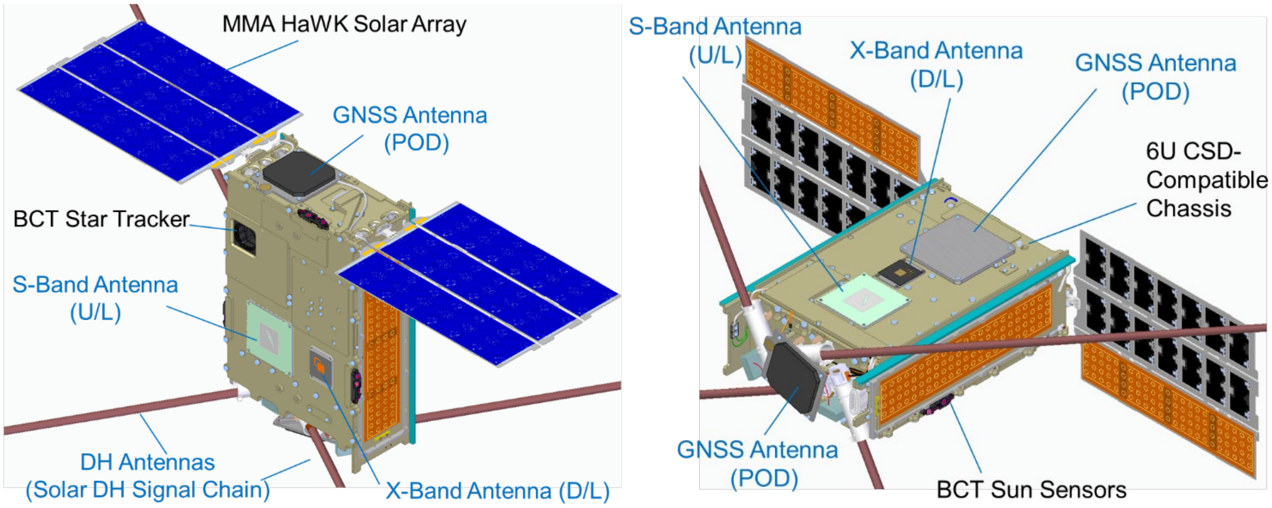

Figure 8. (right) Shows the -X, +Y, +Z faces of the Space Vehicle. (left) Shows the +X, -Y, -Z faces of the Space Vehicle. RF components and their functions are provided for reference.

4.2.1 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.

4.2.2 Attitude, Determination and Control System (ADCS)

The Blue Canyon Technologies (BCT) XACT-50 includes a star tracker, three Sun sensors, inertial measurement unit (IMU), and magnetometer. The reaction wheels are capable of storing several days of disturbance torques, so desaturations will occur once or twice a week as needed.

The BCT XACT-50 is able to control the space vehicle in the nominal deployed state—when all four STACER antennas are deployed. We evaluated the off-nominal cases (1, 2 or 3 STACERs do not deploy) as well, and we confirmed that the BCT XACT-50 can control the SV for all scenarios.

4.2.3 Structure and Dispenser

SunRISE uses SDL's standard 6U CubeSat aluminum chassis, which is compatible with Planetary Systems Corp's Canisterized Satellite Dispenser (CSD). The CSD has flown since 2013 and has over 50 releases without failure. The CSDs will be mounted in pairs on isolators to an interface plate that attaches to an ESPA ring carried by a host spacecraft. Figure 9 shows a notional launch configuration.

4.2.4 Power

SDL uses an off-the-shelf solar array (MMA Hawk), space-rated battery cells, a control board, and a power switching board. The most significant battery pack discharge happens after the space vehicle is dispensed from the CSD; thereafter the state of charge will be maintained well above 50%.

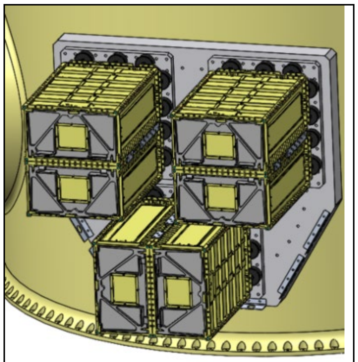

Figure 9. Notional launch configuration. The six CSDs will be mounted in pairs to an interface plate for launch.

4.2.5 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. Innoflight made slight modifications to the SunRISE SCR-106 to ensure compatibility with CCSDS and the Deep Space Network. Patch antennas are mounted on the spacecraft; the X-band patch antennas were built at JPL, and the S-band patch antennas were provided by SDL. There are X and S-band patch antennas on each of the +Y and -Y faces of the spacecraft. This configuration offers near-complete coverage for ground communications.

During our telecom compatibility testing, we saw erratic downlink behavior that caused the DSN receivers to have trouble staying in lock for downlinks. We implemented the typical corrective actions, contacted subject matter experts, consulted with Innoflight, and even replaced the oscillator in one radio, but still did not resolve the instability.

Finally, we pursued less obvious solutions, which led us to a JPL Senior Telecom Engineer, who is familiar with some of DSN's more unusual settings and immediately recognized that our radio is inherently more noisy than deep space radios. She pointed out that Innoflight's SCR-106 is typically used by spacecraft in Low Earth Orbit (LEO) and with near Earth networks, which tolerate noisier systems than those the Deep Space Network typically interacts with. She identified the atypical carrier loop settings DSN needs for SunRISE's radios. After adjusting the DSN settings, the erratic downlink behavior disappeared, and the radios were able to remain locked onto the DSN receivers.

4.2.6 Propulsion

The propulsion units were designed and built by Georgia Tech Research Institute and constructed using additive manufacturing techniques. Due to volume limitations, the system is not a blow-down system, but rather a self-pressurized, two-phase, cold-gas system using inert R-234a as a propellant. (See Figure 6.) It is similar to the design used by the BioSentinel and Lunar Flashlight missions. The plenum is refilled when its pressure drops below 80% of the main tank pressure. The time needed to refill the plenum is ~3 seconds. Maximum firing time for single thruster is about 1.75 seconds at the hot case of 30°C, and the nozzle expansion ratio is 204. The firing time limitation stretches out the time it takes SunRISE to establish the constellation.

SunRISE uses the prop system for 3-axis attitude control (reaction wheel desaturations and stabilization after separation and deployments), and translational maneuvers (orbit insertion and trim maneuvers). It is necessary for the formation and maintenance of the Observatory.

While we expected a propulsion system for a 6U spacecraft would be challenging, our prop system proved to be significantly more problematic than expected. Three major design issues were uncovered relatively late in the development lifecycle: attenuated flow through the system, excessive leak rates, and unpredictable valve stiction. SDL & JPL quickly formed a task force, which brought in subject matter experts from both institutions, to systematically address each design issue and perform additional testing as needed. The propulsion issues are documented in detail in [7]; therefore, they are addressed here at a cursory level only.

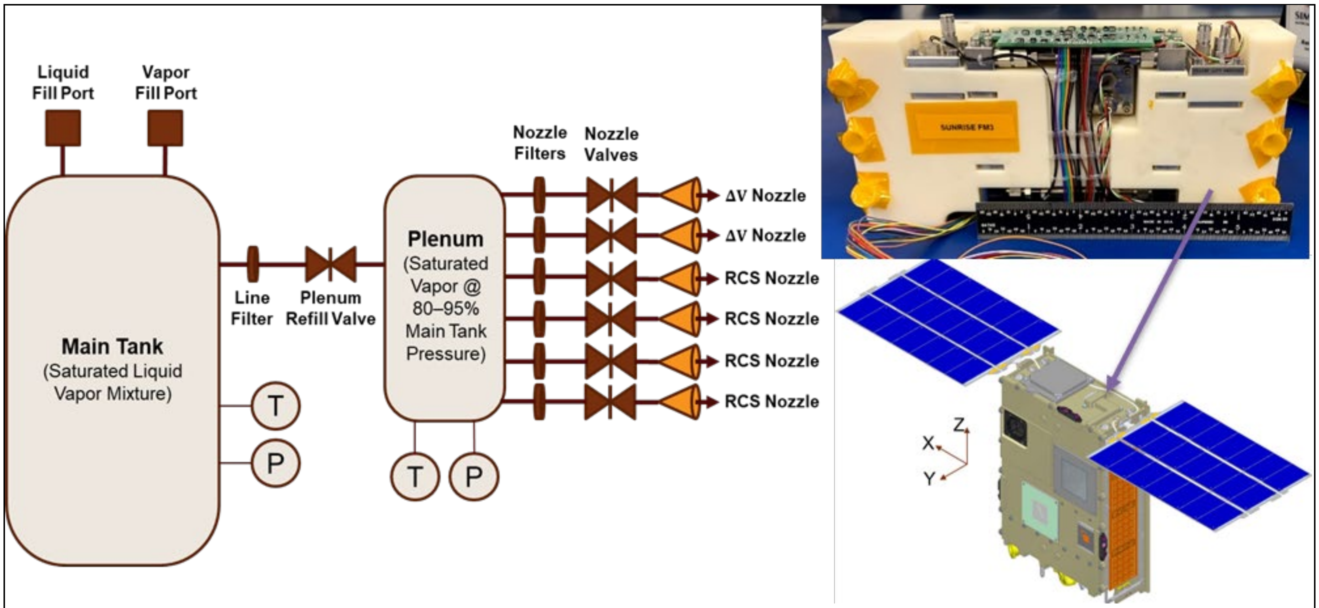

Figure 10. (left) The propulsion system is a self-pressurized, two-phase, cold-gas system using inert R-234a. (It is not a blow-down system.) It is used for both reaction control and translational maneuvers. (upper right) The system was produced using additive manufacturing techniques. (lower right) It is located at the +Z face of the Space Vehicle.

Restricted flow through the system: Some nozzles exhibited low thrust and/or hissing sounds. The root causes were determined to be uncured resin blocking the passages in the tanks and screen filters with out-of-family flow rates. We were able to retire this risk through corrective actions including:

- Producing new tanks.
- Implementing improved tank cleaning, resin-removal, and coating processes.
- Screening flight filters to exclude low-flow units.

Excessive leak rates: Leaks were first detected in the valve manifolds during environmental test using a Freon sniffer as well as mass-loss measurements. Tightening the fittings did not correct the issue. Also, failures were observed at the weld joint of the valve-tube stub interface. The leakage issues were addressed primarily through enhanced workmanship, additional testing for leaks, and adjusting fittings if necessary. There is residual risk that unit-to-unit variations and/or thermal life cycling will cause changes to the leak rates while on orbit. Corrective actions to bring the leak rates into compliance with the requirements included:

- Inspection of the weld-tube stub and valve body.
- Greater control over swaging process, including minimizing the torque on the welded joint.
- 10x visual inspections of the welds.
- 10x Visual inspections of valve tubes and fittings.
- A single experienced technician performed all work on swaged mechanical fittings.
- Detailed written procedure for swaging the fittings.
- Relax the overly conservative system leak-rate requirement from 1 mg/hr to 6 mg/hr freon

Unpredictable valve stiction: It was observed that some valves did not actuate on first attempt. We could not establish a root cause but were able to identify mitigations which should significantly reduce the risk. The mitigations addressed contaminants, valve variability and actuation energy, and problems seen at low temperatures. We carry a residual risk for this issue and will implement operational mitigations as well.

Mitigations include:

- Modified the Drive Electronics Circuit—increased the voltage to the solenoid valves to ~12V.
- Reduced the valve variability by screening for valves that actuated more consistently and at lower voltages.
- Established Operational mitigations such as using “unsticking” pulses prior to large or clean-up maneuvers. This has been incorporated into the flight software and the uncertainty models.
- Careful cleaning and bake-out of the valves and avoiding known contaminants.

4.3 Observatory

The passive formation of the SunRISE space vehicles orbits at GEO + 300 km. This altitude is known as a “graveyard” orbit for obsolete GEO spacecraft. This is a dynamically quiet environment, where effects such as the Earth’s gravity field, tides, and atmospheric drag have little impact.

The space vehicles’ orbits have been designed to oscillate around a reference orbit, with all space vehicle orbits having the same period, to form a radio interferometer. SV separations or interferometric baselines are approximately 10 km when projected into a plane normal to the Sun-SunRISE line.

GNSS precise orbit determinations (PODs) are used, on a weekly basis, to monitor and adjust the orbits as needed to maintain the structure of the interferometer. Orbits are maintained within an approximate 10 km volume to ensure sufficient angular resolution for science purposes. An additional constraint on the navigation team is to keep the risk of collision between the space vehicles 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, because a space vehicle’s position is determined in post-processing from the GNSS POD. However, from a navigation perspective, if allowed to grow without correction, the risk of collision could become unacceptably high.

The mission design and navigation are further detailed in [8].

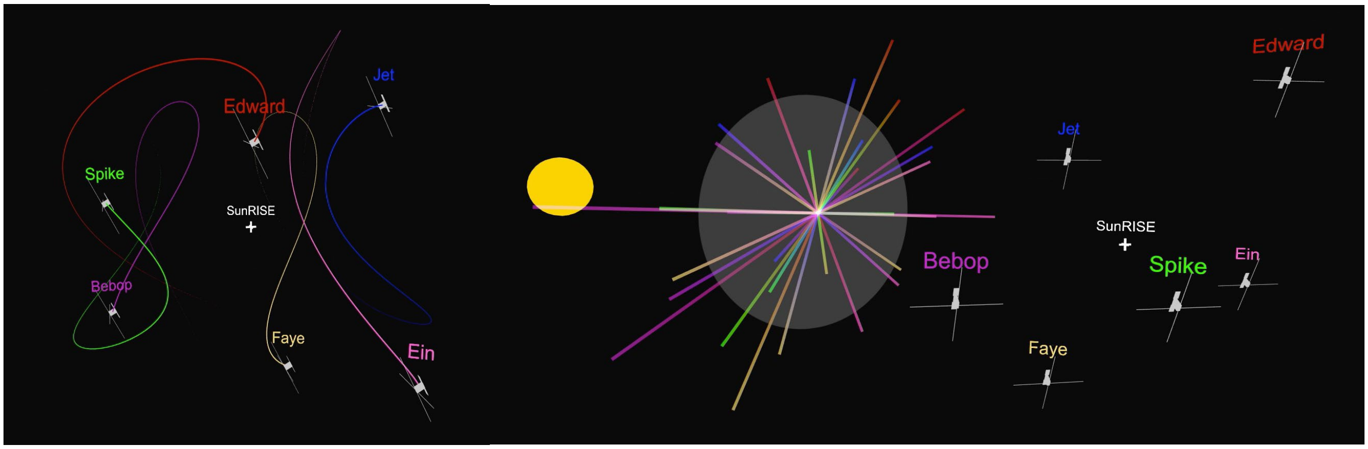

Figure 9. Illustration of the SunRISE Observatory orbits. (left) Portion of the individual space vehicle orbits relative to the reference orbit indicated by the SunRISE marker. Each track shows how the SV has moved over a portion of its full orbit. (right) Formation of the interferometer. The diameter 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.

4.4 Mission Operations System

Operations occurs on a weekly, repeating cycle. In a nominal week, each SV desaturates its reaction wheels once, performs one optional orbital trim maneuver (OTM), and communicates with the DSN during one five-hour pass. The remainder of the time, the SVs are collecting science data.

DSN passes use Multiple Spacecraft per Aperture (MSPA) to downlink from three SVs, simultaneously on unique frequencies per pass to one DSN receiver per SV. This strategy requires two DSN passes per week to communicate with the full constellation. Uplink is handled by a single DSN transmitter; commands are differentiated between SVs by IDs in the command header. Therefore, commanding is sequential to a single SV at a time. The five-hour pass duration is required to downlink all 2.4 GB of data, mostly science, generated weekly by each SV. The required time for uplinks is less than the downlink requirements, so uplink time does not drive the time needed per pass.

During downlinks, the payload is powered off due to thermal constraints. It remains on during desats and orbital trim maneuvers (OTMs).

During each pass, a two-week plan of command products is uplinked to each SV. The plan covers the timeframe beginning immediately after the pass concludes. Week two in this plan is contingency against a missed pass; nominally, commands scheduled for week two will be altered or cancelled during the next week's DSN pass, but in the case of a missed pass, week-two info can keep the Observatory safe. OTMs are only scheduled for the first week of this plan due to uncertainty in orbit prediction, and likewise for desats after two weeks. In contrast, the science payload is provided a four-week configuration on each uplink. The extra two weeks of payload configuration, relative to the command products, extend the duration of valid science data collection without ground contact. Based on expected SV drift rate, science observations can continue with minimal degradation until the four-week cutoff. In other words, navigation drives the communications cadence.

Between passes, the operations team is working at full capacity to process downlinked data, perform health checks, and generate new command products in time for the next pass. Depending on DSN scheduling, the processing period may be as short as three days.

Observatory uptime is critical for meeting SunRISE science objectives. In the context of mission operations, this flows down into a strong requirement for robust procedures and ground tools, especially when combined with only once-weekly DSN contacts. Mistakes, missed contacts, or other anomalies can result in a full week of lost observations, which represents nearly 2% of nominal mission duration. This is one-fifth of the allowed 10% downtime. Clearly, mission operations must be designed to mitigate this possibility. All the factors influencing the Observatory Availability and the challenges to meet the science requirements are detailed in [9], which includes impacts to baseline and threshold missions based on downtimes of various elements of the mission.

Ensuring that mission operations maximizes Observatory Availability is quite challenging when attempting to manage six separate SVs. The vehicles are fully independent from each other, and somewhat independent from the ground. There is no inter-vehicle communication, and all vehicles have onboard fault management with the ability to recover from safe mode without ground interaction. While these attributes help simplify both nominal and contingency operations, SunRISE is far from a "hands-off" mission, yet staffing needs have been minimized through automation techniques. While other missions need multiple staff to operate one spacecraft, SunRISE operates six SVs with a staff of four people. Mission operations, the Ground Data Systems, and their challenges are detailed in [10]. The testing performed and tools developed to meet those challenges are also addressed in [10].

4.5 Science Data System

The key to the SunRISE mission establishing an interferometer is being able to combine the data on the ground. FX Correlator for Interferometry: The estimation of the spatial coherence function, or correlation, employs 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.

5 TESTING the SYSTEM

SunRISE employed many of the typical hardware and software testing. However, as the Instrument is comprised of the 6 payloads on orbit and the Science Data System, we needed a way to test the entire system.

We had to “fly” all six space vehicles at once and flow their data to the SDS to confirm the system works. We created a test plan for an Interferometer Level Performance Test (ILPT). Team members from all organizations and systems needed to participate to successfully demonstrate the system. It took months of planning and a month to actually execute. The test was successful in that we discovered holes and mismatches in the system, but no showstoppers, and we were able to flow data from all six payloads into the SDS to prove out the interferometer.

We demonstrated nominal operations of six vehicles in the science phase of the mission with weekly downlinks and large data volumes. We also demonstrated a subset of critical commissioning phase activities in the extremely high-fidelity test environment of ILPT, and did that on a realistic mission timeline.

ILPT was ultimately a great success for the team. Critical lessons about operating the whole constellation were learned. The most valuable of these lessons was understanding the true challenge of configuration management on the mission. In addition, the team (operators, as well as supporting team members) experienced, for the first time, pain points present in weekly operations. Improvements, which previously seemed small and perhaps not worth implementing, became clear requirements. For example, preparation of file uplink commands had been left as a manual process. This was quickly automated during ILPT after the realization that what had taken 10 minutes in prior tests now took 60 minutes because it needed to be done six times! More details about ILPT are included in [10].

6 CONCLUSION

SunRISE is the first space-based interferometer. It will fly a synthetic aperture equivalent to a >6.5-km monolithic aperture. Four mission operators will operate six space vehicles; this is fewer operators than space vehicles. It identified Science that could be achieved with SmallSat technology. It is blazing the trail for other multi-spacecraft missions and particularly for space-based interferometers.

SmallSats and off-the shelf components should not be discounted for Science missions. Indeed, SmallSats can deliver big results and offer big returns on investment.

The paradigm shift from single-spacecraft missions, to multiple-spacecraft missions, will take some getting used to. It will also take some creativity as we learn how to test and manage these new missions, but we are well on the way to a new paradigm.

Figure 11. The SunRISE Space Vehicles are in storage, awaiting their ride to space.

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