32nd URSI GASS, Montreal, 19–26 August 2017

The Sun Radio Space Imaging Experiment (SunRISE)

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Abstract

Radio emission from coronal mass ejections (CMEs) is a direct tracer of particle acceleration in the inner heliosphere and potential magnetic connections from the lower solar corona to the heliosphere. Energized electrons excite Langmuir waves, which convert into radio emission at the local plasma frequency, with the most intense acceleration thought to occur within 20 R_S. The capability of ground-based radio arrays to track this radio emission is limited by ionospheric absorption ($\nu \gtrsim 15$ MHz) to altitudes less than about $3\,R_S$. The state of the art for tracking such emission from space is defined by single antennas (Wind/WAVES, Stereo/SWAVES), in which the tracking is accomplished by assuming a frequency-to-density mapping; there has been some success in triangulating the emission between the spacecraft, but considerable uncertainties remain. The Sun Radio Imaging Space Experiment (SunRISE) mission concept would be a constellation of small spacecraft operating as an interferometer designed to localize and track radio emissions in the inner heliosphere. Each spacecraft would carry a receiving system for observations below 25 MHz, and SunRISE would image CMEs more than a few solar radii from the Sun.

1 Introduction

Particle acceleration is one of the most pressing questions in Heliophysics, as identified in the 2013–2022 Decadal Survey [1]. The phenomenon occurs in plasmas throughout the cosmos: within planetary magnetospheres, at the termination shock, at stars, and at supernova shocks. Despite its importance, still unresolved are the sources of solar energetic particles (SEPs) within the heliosphere and how some SEPs are able to spread quickly to a broad range in solar longitudes. Solar Probe Plus [2] will fly within 10 R_S and measure plasma, SEPs, and coronal mass ejections (CMEs), but will not measure particles as they are first accelerated [3]. The SunRISE mission concept aims at addressing this limitation by imaging the radio emission produced by particle acceleration source regions in the low corona and by energetic particles as they travel interplanetary space.

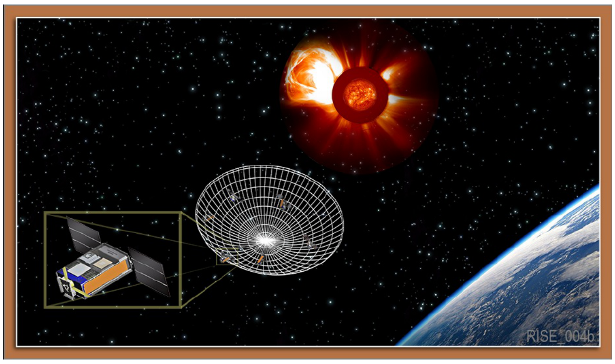

Figure 1. Artist's impression of the SunRISE constellation of small spacecraft forming a synthetic aperture and observing a solar radio burst.

Solar radio bursts are produced when electrons energized to a few to 20 keV flow through coronal plasma at more than 2 R_S. The SunRISE mission concept would observe Type II and III bursts (Figure 2; [4, 5]). These bursts encode detailed information about the location and transport of accelerated electrons. The SunRISE mission concept would have two objectives. Objective O1 would be to discriminate competing hypotheses for the source mechanism of CME-associated SEPs by measuring the location and distribution of Type II emission relative to expanding CMEs over the range 2 R_S–20 R_S where the most intense acceleration occurs (Figure 3).

The most intense and longest duration prompt SEP events are associated with CMEs [6], and there is a strong obser-

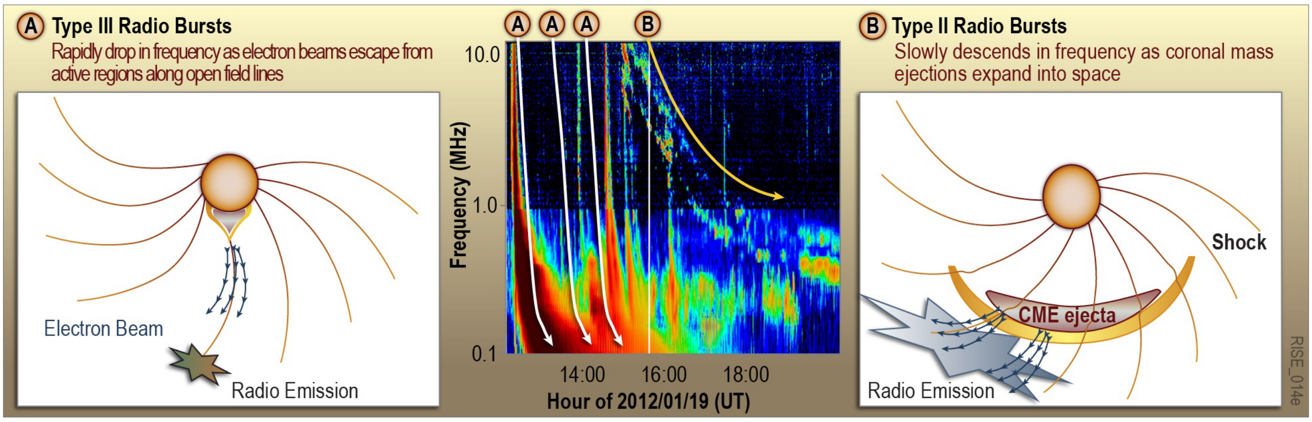

Figure 2. SunRISE uses Type III (A) and Type II (B) radio bursts to track particle transport and acceleration within the inner heliosphere. The middle panel shows the state of the art, a dynamic radio power spectrum from the Wind spacecraft illustrating a storm of Type III bursts preceding a several hours long Type II burst from a CME.

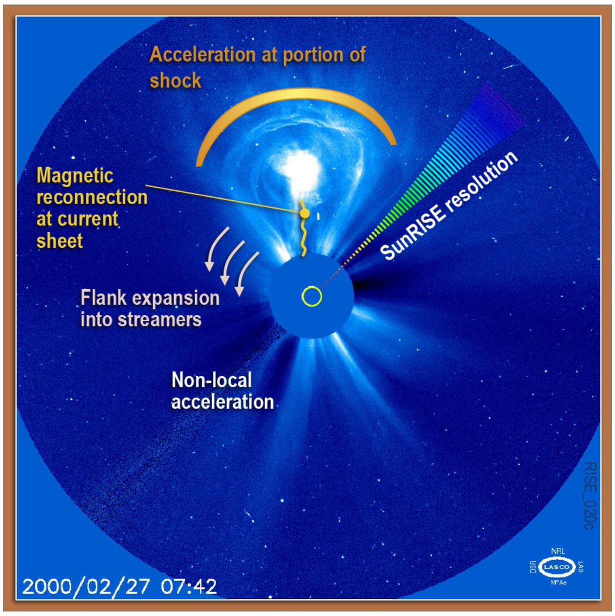

Figure 3. SunRISE would measure the location and distribution of radio emission with sufficient temporal, spatial, and frequency resolution to separate between shock, flank, reconnection, and non-local hypothesis for the source of Type II emission.

vational association between the production of SEPs by a CME and the occurrence of Type II bursts [7]. Particle acceleration may be due to coronal shocks or compressions driven by CMEs, by magnetic reconnection behind expanding CMEs, or by stochastic acceleration mechanisms operating throughout the corona (Figure 3). A lack of observations of the acceleration process operating in space and time makes it difficult to distinguish between these models. The interpretation of associated SEPs in interplanetary space is further complicated by the unknown role of transport effects between the CME and the observer: Is a slowly increasing intensity of SEPs due to an increase in the efficiency of the acceleration mechanism at the source, or a filtering effect due to the slow diffusion of SEPs along and across a complex coronal and interplanetary magnetic field?

Objective O2 would be to determine if a broad magnetic connection between active regions and interplanetary space is responsible for the wide longitudinal extent of some SEPs by imaging the field lines traced by Type III bursts from 2 R_S–20 R_S. Observations with the STEREO spacecraft, combined with near-Earth measurements, have shown surprisingly wide longitudinal distributions for SEPs [8, 9], including a rapid spread over 360° in longitude observed in CME-associated events and events observed near Earth for which the sources are on the backside of the Sun. Whether such distributions are a result of particle transport or intrinsic to the acceleration region remains to be determined.

Generally, SEPs accelerated during solar flares are relatively narrowly confined ($\lesssim 40°$ longitude). However, multi-spacecraft observations have revealed a number of ^{3}He-rich events extending well over 60°, and even over 130° [10]. Explanations related to field-line meandering (limited to $< 10°$, J. Giacalone, private communication), field-line spreading from the photosphere to the corona [10], or field-line corotation [9] have proven insufficient. One of the most promising proposed mechanisms relies on reconnection within the complex magnetic topology that can develop when a coronal hole is near a flaring active region [11, 12, 13].

In order to achieve these science goals, the SunRISE mission would have to resolve the centroid and spread of radio burst emission in the sky as a function of frequency and time in order to relate the location and motion of the energized electrons responsible for the bursts to CME structures (O1) or coronal magnetic field lines (O2). Specific mission requirements include covering the frequency range of 0.1 MHz–25 MHz, in order to cover a sufficient range in distance from the Sun; an orbit well above the Earth's ionosphere; the capability to observe for several hours, in order to track Type II bursts; the capability to localize the radio emission to better than 1/3 of the diameter of a CME; and a mission duration of at least 6 months, in order to operate long enough to observe multiple Type II bursts.

2 Spacecraft and Mission Description

Interferometry is a well-established technique for observations of both the Sun and other celestial sources. Ground-based synthetic apertures have been used to study solar radio emission [14, 15, 16], but these observations have been limited to low altitudes ($< 3R_S$) because of the Earth's ionosphere ($\nu \gtrsim 15\,\mathrm{MHz}$).

SunRISE would consist of six identical spacecraft, each with a 6U CubeSat form factor (10 cm × 23 cm × 36 cm), forming an observatory in a circular orbit slightly above geosynchronous orbit (GEO). While all six spacecraft would be operated in formation, only five are required to obtain the required localizations, providing resiliency to spacecraft failure. Alibay et al. [17] describe the spacecraft and mission design; here we summarize salient details.

Each SunRISE spacecraft would have two crossed, electrically short dipoles (Figure 4), deployed once on orbit. A front end would condition the received radio emissions by amplifying and filtering, the conditioned signals would be digitized, and a polyphase filterbank would transform the digitized signals into the frequency domain [18]. This signal chain is robust against likely interference, as it is based on the receiver being used for the Department of Defense DHFR mission, which is designed to be Galactic noise dominated in low-Earth orbit, and other resource requirements for the antenna elements and receiver are modest.

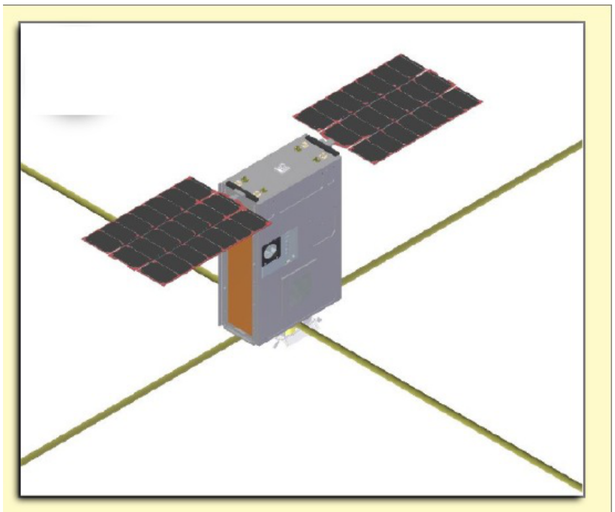

Figure 4. Artist's impression of a SunRISE spacecraft, with both the solar radio antenna and the solar panels deployed.

The GNSS signal chains would provide time stamps for when the solar radio burst data were acquired and from which the relative locations of the individual spacecraft can be determined. The SunRISE GNSS signal chain would inherit its major functions from the Cio payload on the Cicero mission and the NASA-sponsored TriG receivers [19]. In this concept, on-board software would use a fast Fourier transform (FFT) to determine the carrier phase and pseudorange to visible GNSS satellites. These data would be transmitted to the ground, where they would be post-processed to generate orbit determination solutions. Real-time navigation solutions would not be required.

The SunRISE mission would be enabled by the use of an FX-style correlator to form the visibility data [18], which would both reduce the downlinked data volume by orders of magnitude and shift substantial processing to the ground. The "F" portion of the FX correlation is formed on-board each spacecraft via the polyphase filterbank. The cross-multiplication amongst all unique pairs, the "X" portion, occurs on the ground.

A two-step procedure would be used to localize radio emission. (1) The visibility data are Fourier inverted to form an image. (2) The location of the radio emission is determined by fitting a simple model (Gaussian), using the location of the peak in the image as an initial estimate for the fit. Software to Fourier invert the visibility data and to fit for the position of radio emission is well developed and routinely used to process arrays consisting of tens of antennas with thousands of frequency sub-bands [20].

The spacecraft would be launched as a secondary payload and inserted into their initial orbit by a host satellite, forming a passive formation for which only biweekly correction maneuvers are required to maintain 0.5 to 12 km baselines and avoid collisions. Once the spacecraft enter their nominal science operations mode, they are operated using a straightforward, repeating 2 week pattern. In a typical week, there is only a 5 hr interval, during with each spacecraft desaturates its reaction wheels and downlinks to the Deep Space Network (DSN). For the majority of a 2 week cycle, the solar arrays and solar radio antennas are Sun-pointed, with the instrument turned on and collecting data.

3 Conclusion

While ground-based interferometers have existed for some time, space-based interferometers have been cost prohibitive thus far. The SunRISE mission concept would leverage the recent advancements in CubeSat technologies and to obtain a low-cost mission concept that would address important goals of the Heliophysics community. This concept, which would be low cost and with a rapid development cycle, could serve as a stepping-stone for the demonstration of space-based interferometry. Indeed, space-based radio astronomical arrays can address a wide range of scientific questions that go beyond those addressed here, ranging from planetary and extrasolar planetary magnetospheres and particle acceleration in astronomical sources to potentially searching for the signatures of the first stars. Being able to demonstrate the capabilities of such an observatory with SunRISE could serve as a proving ground and an enabler for more complex future missions.

4 Acknowledgements

Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics & Space Administration.

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