Title: SOLARA/SARA: Solar Observing Low-frequency Array for Radio Astronomy/Separated Antennas Reconfigurable Array

Primary Point of Contact (POC): Mary Knapp
Organization: Massachusetts Institute of Technology (MIT)
POC email: mknapp@mit.edu

Need

Viewing the universe in a wide range of wavelengths (from gamma to radio) has greatly advanced astronomy by providing new perspectives on known phenomena and revealing previously unknown objects and events. A crucial segment of the EM spectrum remains unexplored, however. Very low frequency radio waves (~30MHz – 30KHz) are reflected by the Earth's ionosphere and cannot be observed from the Earth's surface. To date, there have been no significant astronomical surveys in this three-decade spectral band. Astronomical observations in this unexplored region of the spectrum will enhance the study of the sun, solar system planets, exoplanets, ancient galaxies, the interstellar medium, and perhaps reveal entirely new phenomena[1].

The long wavelengths involved in such a survey require a large aperture to achieve reasonable resolution. An instrument intended to observe this low frequency band must be above Earth's atmosphere to avoid ionospheric interference. These requirements make a space-based interferometry array the logical choice for exploring very low-frequency phenomena. Small satellites are ideal for such a mission because their manufacturing and launch costs are low.

Because the SOLARA design requires already the presence of multiple spacecraft, it is also the ideal test platform for a distributed communication system. The Separated Antennas Reconfigurable Array (SARA) would use the SOLARA platform to test a MIMO (Multiple Input Multiple Output) antenna system in space. Such an antenna system would be critical for small satellite exploration beyond Earth orbit.

SOLARA/SARA offers the opportunity to conduct groundbreaking science while also using the same platform to demonstrate technologies that will significantly expand the capabilities of CubeSats and small sats.

Mission Objectives

The Solar Observing Low-frequency Array for Radio Astronomy (SOLARA) would address this significant knowledge gap by serving as a pathfinder space-based radio interferometry array.

SOLARA's primary objective would be solar observations. Coronal Mass Ejections (CMEs) are a critical target for study because they pose a significant danger to satellites, humans in space, and power grids on the ground. SOLARA will enhance CME tracking and contribute data on heliophysics and solar weather. SOLARA's complete mission objectives are as follows:

1. **Observe temporal and spatial evolution of solar weather and its interaction with Earth's magnetosphere**.
    a. Temporal resolution of 1 minute
    b. Spatial resolution of 1 arcminute
    c. Track CMEs and estimate geoeffectiveness[2] (likely damage upon reaching Earth)
2. Produce all-sky map in three bands between 30MHz and 30kHz
    a. Spatial resolution of 0.5-1°
    b. Attempt to identify high-redshift galaxies
3. Observe Jupiter's magnetospheric radio emissions
4. Observe known cosmic radio sources (radio pulsars, radio galaxies) and interstellar plasma
5. Attempt observation of exoplanetary magnetospheric radio emissions

SARA will use small, low power patch antennas integrated into each unit of SOLARA to form a high EIRP (Equivalent Isotropic Radiated Power) distributed antenna by combining the signals from each individual antenna in phase. A synthesized beam composed of many spacecraft antennas will allow higher data rate communications for CubeSats without the need for deployable/inflatable antennas or high power amplifiers. SARA will demonstrate technology that could enable a group CubeSats with simple, low power antennas to communicate effectively from far beyond Earth orbit.

The mission objectives for SARA are as follows:

1. Test the technology of MIMO antenna system in space.
    a. Measure the effect of time delay between the different patch antennas and quantify the effect of the delay on the quality of the signal.
    b. Assess the feasibility of a MIMO system in space with respect to the challenges associated with the formation flight of the CubeSat constellation.
2. Demonstrate the possibility of increasing the communication data rate of at least one order of magnitude with respect to traditional CubeSat communication systems.

Concept of Operations

Pre-launch: Array elements will be designed, constructed, and tested at MIT as part of the authors' graduate thesis work/postdoctoral research. A single unit will be tested in low Earth orbit (LEO) as a demonstration before the remaining constellation members are constructed. Flight models will be built and delivered to launch organization.

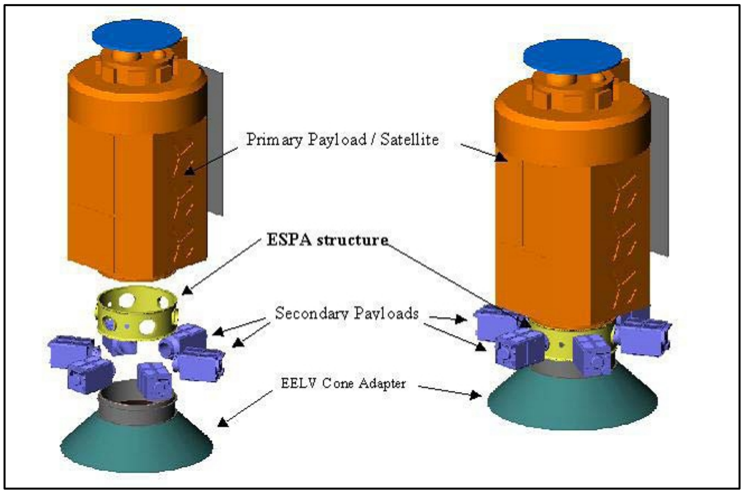

Figure 1 ESPA system showing primary payload (orange), ESPA ring (yellow), P-POD clusters (blue) and adapter ring (green). Each P-POD cluster would hold 2-4 spacecraft and its own propulsion system.

Launch: Flight units will be delivered to launch vehicle and loaded into Poly-PicoSatellite Orbital Deployer (P-POD). Sets of two (or more) P-PODs will be attached to the ports of an EELV Secondary Payload Adapter (ESPA) ring by means of an adapter plate (see Fig. 1). Once the primary payload's orbit is reached, the P-PODs and adapter plates will separate from the launch vehicle. A small thruster will deliver each set of P-PODs to their final orbit. The P-PODs will then deploy the array elements into the array formation (a rough sphere with ~10 km diameter). See Fig. 2 for deployment sequence.

Nominal Space Operations: When the array is in place, it will go through a check-out procedure and then begin monitoring the sun. Signals from ground stations on Earth will serve to synchronize timing aboard each element. Communication will happen when ground stations are in view (choice of ground stations depends on the sponsoring institution). Small thrusters onboard each spacecraft will provide small corrections to keep the general shape of the array intact. Decommissioning procedures will depend on the chosen orbit (see **Orbit/Constellation Design**).

Key Performance Parameters

SOLARA and SARA are well suited to a combined mission because both require precise measurement of the distances between each spacecraft as well as time synchronization.

SOLARA:

1. Angular (spatial) Resolution and spectral resolution
2. Sensitivity
3. Dynamic range
4. Accurate baseline measurement (<1/10λ)
5. Precise time synchronization

SARA:

1. Gain and beam width
2. EIRP
3. Data Rate
4. Time delay for synchronization
5. Phase accuracy

Space Segment Description

SOLARA/SARA will be composed of at least 12 individual spacecraft. Each spacecraft will generate its own power, control its attitude, collect science data, and communicate with other array elements and with the ground. For redundancy and single point failure avoidance, the array will not depend on any single element, making it highly fault tolerant. Each element of the array will monitor a frequency band and transmit its data back to Earth. The data from each satellite will be combined on the ground along with information about the separation between each element (baseline) using proven interferometry techniques.

Radio science: Two sets of long deployable dipole antennas will be used receive signals of interest. The antennas will be made from a shape memory material (like spring steel) that will extend to full length when the spacecraft is deployed. The length of the antennas will be determined by a trade study between sensitivity and mass/volume constraints, but they will likely be 1-5 meters in length. The dipoles will be mounted orthogonally to each other. Signals from the antennas will be amplified and digitized by a commercially available receiver and then stored in FLASH memory for transmission to Earth.

Avionics: Data handling, attitude control, and housekeeping procedures will be conducted by a space-rated FPGA. FLASH memory will be used for data storage between communication passes.

Communications: Each spacecraft will communicate in S-band using a patch antenna. The communication system will also be used for time synchronization. A signal from Earth and/or one array element will be used to phase lock oscillators on each spacecraft. Communications signals to and from Earth will also be used to determine motion of individual spacecrafts through Doppler analysis.
SARA will make use of the patch antennas on each spacecraft to synthesize a composite beam of higher power and gain than any individual array element is can produce on its own. SARA will greatly increase the data downlink rate to Earth, which will increase the science return of the mission. Since SARA is an experimental system, each array element will be able to communicate with the Earth on its own, but at a lower data rate, as a back-up communications solution.

Ranging: Baselines between array elements will be measured by an onboard ranging system in each spacecraft as well as through communication with the ground. The onboard system will use a broadcast tone to measure distance from one satellite to another. The inter-satellite system will determine the relative positions of each array element, but not to absolute distance to Earth or the rotation of the array relative to Earth. Earth-based ranging, based on analysis of communications, will be used to determine absolute orientation of the array.

Thermal: The possible orbits for SOLARA (see **Orbit/Constellation Design: Orbits)** are relatively thermally stable since they place SOLARA in sunlight most of the time. Solar heating can be used to passively heat sensitive electronics. The only active thermal control needed would be small resistive heaters for times when SOLARA passes through an eclipse (caused by the Earth or the Moon). Thermal sensors would be placed throughout the spacecraft for monitoring purposes. Reflective paint on portions of the spacecraft exposed to sunlight will prevent overheating.

Power: Deployable solar panels (four deployed and one body mounted) would be used to generate ~30 W power for each spacecraft. Several batteries will store power for use during sunlight interruptions.

Structure: Each spacecraft will be a three-unit CubeSat with dimensions 34 cm x 10 cm x 10 cm. The chassis will be purchased from a CubeSat supplier and slightly modified to accommodate custom parts like the deployable antennas and propulsion system.

Attitude Control System (ACS): The primary attitude control system will consist of reaction wheels and thrusters. Reaction wheel units, like the MAI-400, are available off the shelf for CubeSats. Several propulsion systems are under development that could provide both delta-V and reaction wheel desaturation (see **Propulsion**). Rate gyros and sun sensors would provide input for sensing and estimation. Attitude will be controlled to 1-2°.

Propulsion: Propulsion (~1 m/s total lifetime delta-V) is needed to maintain the general spherical shape of the constellation. A miniaturized butane thruster is one example of an off-the-shelf propulsion solution for Cubesats[3].

Smaller systems, including ionic electrospray patch thrusters, are in development and are expected to fly within the next 1-2 years[4] and are already being incorporated into missions under development. A small rocket (solid or monopropellant) or an array or electrospray patch thrusters will be used to transfer the P-POD packages from the ESPA drop-off location to the final orbit of the array.

Orbit/Constellation Description

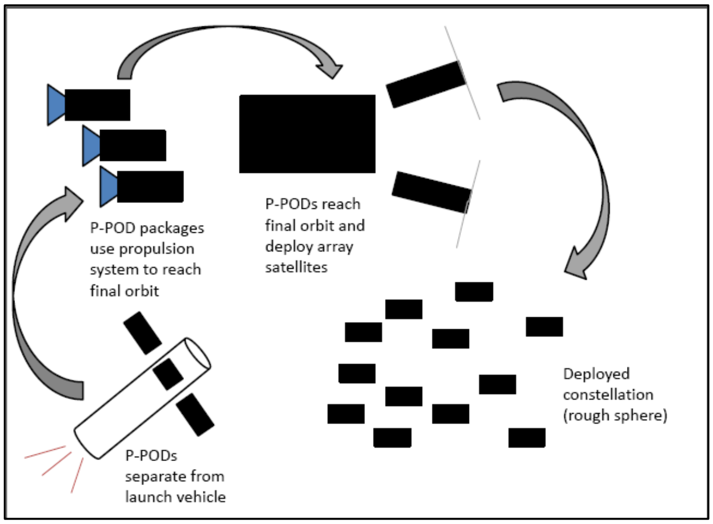

Figure 2 SOLARA deployment sequence. P-POD bundles separate from the launch vehicle then engage their propulsion systems to move to the final SOLARA orbit. There, the P-PODs release the array units into a roughly spherical constellation.

Constellation: A constellation architecture is required for SOLARA/SARA to achieve its mission goals. SOLARA uses well-known interferometry techniques to create a synthetic aperture much larger than individual spacecraft. Each element of the array is part of a sparse aperture as large as the largest separation between elements in the constellation. Individual satellites will be deployed in a roughly circular formation with a diameter between 10 and 100 km. At least 12 satellites are required to provide sufficient sensitivity and diverse baselines[5]. The baselines need not be precisely controlled – only precisely measured. Interferometer baselines must be known to a small fraction (1/10 – 1/16) of the wavelength under study, so the long wavelengths measured by this array (10 m – 10 km) only require measurement precision of ~1m to 1km. Baseline measurements along with precise timing information are used to combine signals from all elements of the array to create a synthesis image. Figure 2 shows the constellation deployment sequence.

The baseline measurement and time synchronization needed to achieve the SOLARA science goals will also enable the SARA communication system. Baseline measurements will be used to adjust the phase of the signal from each spacecraft's patch antenna to form a composite beam.

Orbit: Radio astronomy, especially at long wavelengths and low intensities, is highly sensitive to terrestrial radio noise contamination. SOLARA would need to be placed as far as possible from the Earth. One location which has been considered for a low-frequency radio array is the far side of the Moon[1]. SOLARA could be placed in a halo orbit around Lunar L2 (2nd Lagrange point). Halo orbits are relatively stable and would not require significant station keeping and the Moon would provide protection from terrestrial radio noise. Alternately, SOLARA could be placed in a distant retrograde orbit (DRO)[5]. DROs are very stable (minimal stationkeeping) and the ~1 million km separation between SOLARA and Earth would greatly reduce radio noise. If neither of these orbits are obtainable with available propulsion systems, SOLARA could be placed in an easily obtainable high Earth orbit (GEO), but would sacrifice some data quality due to the proximity of the Earth. Active deorbiting is not necessary since the preferred orbits from the constellation are far from Earth and interaction with Earth-orbiting spacecraft is highly unlikely. If a GEO orbit is chosen, a small fuel reserve will be maintained for deorbiting purposes.

Implementation Plan

Organization: SOLARA/SARA is in the very early stages of conceptual development, so its organizational structure will depend on funding sources. The SOLARA team would be led by graduate students and postdoctoral researchers with oversight and advice from MIT faculty. Undergraduates will be invited to participate in research and development for SOLARA. The university structure keeps labor costs low while ensuring a skilled and eager workforce. A partnership with a NASA center, perhaps Goddard Space Flight Center, and/or private industry will be sought.

Cost: SOLARA's very early development stage makes cost estimation difficult. Current 3U CubeSat systems cost roughly $500,000 for design, testing, and components (labor not included). Taking the unique propulsion/deployment system needed for SOLARA as well as significant testing and some development, a reasonable margined estimate for one SOLARA element is $1-2 million. Units produced after the prototype is built and tested (and possibly flown) will likely cost significantly less, so a conservative estimate for the constellation of ~12 satellites (again, not including labor costs) is $10-15 million (including launch). It is important to note that NASA and other agencies have developed concepts like SOLARA (ALFA, SIRA), but those concepts were not selected because of high cost and perceived high risk. The use of CubeSats significantly mitigates both issues. Higher risk is acceptable in CubeSat missions, partially because costs are significantly reduced by the standard CubeSat form factor, rideshare launches, and off-the-shelf subsystems.

Table 1 SOLARA/SARA Schedule

Conceptual Design	Jan. 2012 – Jan. 2013
Engineering model construction and test	Jan. 2013 – June 2013
Flight model	December 2013
Launch prototype	2014
Constellation construction	2015
Constellation launch	2016-2017

Schedule: Table 1 shows a high level schedule for SOLARA. As with cost and organization, the schedule is somewhat flexible at this stage of development.

Risk: The top five risks for SOLARA are listed below:

1. *Funding*. SOLARA/SARA is a high risk, high reward project because it combines several new technologies in a novel way. The science and engineering rewards will be significant if it succeeds. However, high risk projects are often not attractive to funding organizations.

2. *Launch opportunities*. SOLARA/SARA proposes a novel use of two secondary payload systems. These have never been used in combination, so launch vehicle owners may be hesitant to add SOLARA to their vehicle because of risk to the primary payload. Extensive testing will be needed to assuage these concerns.

3. *Propulsion*. Propulsion systems for CubeSats are relatively new and would introduce risk to the system. Significant testing would be required for flight qualification and risk reduction. MIT's Space Propulsion Lab is leading efforts to develop electrospray thruster units for CubeSats, giving the SOLARA team the benefit of institutional knowledge and expertise in this area as well as early access to the technology.

4. *Time synchronization*. Maintaining absolute and relative timing accuracy between Earth and all elements of the array is a significant technical challenge. High quality oscillators may break mass and cost budgets, although micro-scale atomic clocks are rapidly becoming a reality.

5. *Data processing*. Aggregating data and processing it to produce an aperture synthesis image with novel data acquisition techniques will take significant research and modeling. While interferometric techniques are well understood and have been used in ground-based systems for decades, these techniques are undeveloped in space. Downlinking all the accumulated data given a limited link budget will present an additional challenge. The SARA communication system, if demonstrated successfully, will significantly mitigate this risk.

References

1. Jester, S. and Falcke, Heino. "Science with a lunar low-frequency array: From the dark ages of the Universe to nearby exoplanets." New Astronomy Reviews, Vol. 53, Issue 1-2, pp. 1-26. (2009)
2. Warmuth, A. and Mann, G. "The Application of Radio Diagnostics to the Study of the Solar Drivers of Space Weather, Lect. Notes Phys. **656**, pp. 51-70 (2005).
3. Mueller, J., Hofer, R., and Ziemer, J. "Survey of Propulsion Technologies Applicable to CubeSats". Proc. 57th JANNAF Propulsion Meeting. (2010).
4. Lozano, P. and Courtney, D. "On the development of high specific impulse electric propulsion thrusters for small satellites." Madeira, Portugal, June 2010.
5. MacDowall, R. J. et. al. "Solar Imaging Radio Array (SIRA): a multispacecraft mission". Enabling Sensor and Platform Technolgies for Spaceborne Remote Sensing. Proc. SPIE, Vol 5659, pp. 284-292 (2005).