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

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Abstract: SOLARA/SARA is a space-borne radio aperture synthesis interferometer which will observe frequencies from 30 kHz to 30 MHz. Earth's ionosphere is completely or partially opaque at these wavelengths, so ground-based observations are not possible. SOLARA will be able to track dangerous solar storms (such as coronal mass ejections) as they approach the Earth and predict the severity of the storm when it arrives. SOLARA has a number of other astronomical applications as well, ranging from exoplanets to fossil radio galaxies. SOLARA is an array composed of 20 6U spacecraft arranged in a rough 10-100 km sphere at the first Earth-Moon Lagrange point. SARA is SOLARA's communications system. SARA will conduct inter-spacecraft ranging as well as transmit data to Earth by combining signals from patch antennas on each CubeSat in the SOLARA array into a single high-gain beam. SOLARA will collect data using a set of 6 m dipoles and a distributed correlator for aperture synthesis imaging. SOLARA/SARA is an ambitious project, but it has the potential to open up a new window on the universe by mapping the sky in an unexplored region of the EM spectrum.

1. INTRODUCTION

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 (~30 MHz – 30 kHz) are reflected or severely attenuated by the Earth's ionosphere and cannot be observed from the Earth's surface. To date, the only space missions to investigate this spectral band have been single spacecraft missions [1] with very low resolution. A distributed array of small spacecraft place 10s or 100s of km apart can achieve much higher spatial resolution than a single spacecraft at a fraction of the cost. High spatial resolution imaging in the unexplored 30 MHz to 30 kHz region of the spectrum (herein referred to as LF[1]) will enhance the study of the sun, solar system planets, exoplanets, ancient galaxies, the interstellar medium, and perhaps reveal entirely new phenomena [2]. The study of solar weather is of critical importance because it will enable better prediction of the arrival time and potential harm caused by solar storms.

1.1 Scientific Motivation

Society is becoming ever more dependent on aging and overburdened power grids and satellite communications technology. Both space-based communications and ground-based power delivery systems are vulnerable to disturbances and damage caused by solar weather events. In September

[1] Although the band described actually spans LF, MF, and HF frequency bands (ITU 5-7), in this paper LF will be used to generically refer to the 30 MHz to 30 kHz portion of the EM spectrum.

1859, a huge coronal mass ejection (CME) caused a geomagnetic storm of epic proportions [3]. Telegraph stations, the most advanced electrical technology at the time, caught fire due to the huge current surges induced by the storm. Aurorae could be seen as far south as the Caribbean. More recently, in October 2003, a CME knocked out power to thousands of people in Sweden [4]. If a solar storm like the one in 1859 were to hit the Earth without warning today, the consequences to the world economy as well as individuals would be severe.

Current solar observatories can image flares and CMEs as they erupt from the sun's surface, but quickly lose the ability to accurately image or track these disturbances as they leave the sun and enter interplanetary space. As charged particles from flares and CMEs travel through the interplanetary medium, the often drive shocks ahead of them. These shocks emit bursts of radio waves which reach the earth before the particles that emitted them. A subset of these radio bursts, known as Type II bursts, are a good indicator that the approaching solar weather is particularly severe and hazardous to technology on and above the Earth. Type II bursts can also be used to track the path and speed of an approaching CME or other space weather event. Photons take 8 minutes to travel from the Sun to the Earth, but CMEs can take anywhere from 18 hours to several days so observations of Type II radio bursts would give forecasters on the Earth at least 24 hours warning of the approach of a dangerous CME. The combination of LF radio imaging of CME shockwaves with existing visible, UV, and X-ray data will significantly improve space weather predictions and will better inform preparations for geomagnetic storms [5].

In addition to the urgent need to better protect the Earth from space weather, LF radio observations will contribute to the fundamental understanding of heliophysical processes. Observing radio bursts from the sun will enhance knowledge of the physical processes taking place in the Sun's corona and the mechanisms by which flares and CMEs form and leave the Sun [5].

Heliophysics and space weather are far from the only science application for SOLARA. There are four other strongly magnetic planets in the Solar system besides the Earth. Studies by Voyager and other craft have provided information about the nature of the giant planets' magnetic field structures, but there is much more to be learned [6]. An imaging instrument that can pinpoint the source of radio bursts will add significantly to our knowledge of the interior structure and dynamo mechanics of the outer planets.

Studying the radio emission profile of the outer gas planets in the LF band will inform searches for the radio emissions of extrasolar planets [7]. Low frequency radio observations have the potential to both identify exoplanets and aid in the characterization of the planets' interiors. At low frequencies, planetary radio emission is the same order of magnitude as stellar emission so a search for bright sources near solar-type stars could turn up previously undiscovered planets. See Figure 1. Exoplanetary radio emission also offers a unique window on the interior structure of these planets. Magnetic field studies are currently the only method to study the interiors of planets outside of this solar system [8]. In the

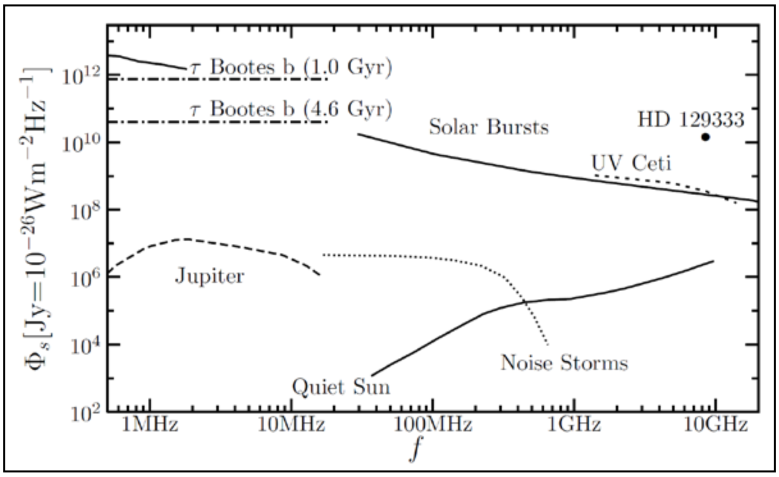

Figure 1 – Comparison of radio flux from magnetic planets in the Solar system, the Sun, and theoretical flux from the exoplanet τ Boo. All fluxes are scaled as if the sources were at 1 AU. Adapted from [9].

search for an Earth-like planet outside the solar system, the presence or absence of a magnetic field will be a key indicator of habitability.

In addition to heliophysics and planetary science, there are numerous potential science goals ranging from studies of the interstellar medium to radio fossil galaxies and the "dark ages" of the universe. For a detailed discussion of these possibilities, see [2]. SOLARA's primary science goals are primarily within the local neighborhood (solar system and nearby exoplanets), but SOLARA's high resolution map of the radio sky will be of interest to galactic and extragalactic astronomers as well. Historically, each new portion of the EM spectrum that has been mapped has led to new and unexpected discoveries. SOLARA has the potential to expand our knowledge of the universe in a similar way by opening up a new vista.

1.2 Technical Motivation

The long wavelengths (10 m to 10 km) SOLARA will be observing require a very large aperture to achieve reasonable spatial resolution. Angular resolution scales as $\theta = \lambda/D$, where λ is the wavelength being studied and D is the effective aperture diameter of the instrument. For long wavelengths, a radio telescope must have an effective diameter measured in km to achieve sufficient resolution to image compact sources like the sun and giant planets. The only way to achieve an aperture of this magnitude is to use many smaller receivers distributed in space to form an interferometric sparse array. Furthermore, an instrument intended to observe this LF band must be above Earth's atmosphere to avoid ionospheric interference. These requirements make a space-based interferometry array the only choice for exploring LF astronomical phenomena. Small satellites are ideal for such a mission because their manufacturing and launch costs are lower than traditional monolithic missions.

The architecture required for SOLARA science goals (multi-satellite array, inter-spacecraft ranging and time synchronization) is a natural fit for the Separated Antennas Reconfigurable Array (SARA) experiment. SOLARA is therefore two missions in one: a radio science mission and an experimental communication mission. SARA will use the SOLARA constellation as a platform to test the technology of MIMO systems in space. Virtual arrays of antennas which result from space diversity combination of different antenna systems have been developed for Earth applications. The fundamental idea is that multiple antennas can be opportunely aggregated to form a bigger array by combining the signal in phase. These systems can be developed easily for Earth applications because the different assets (antennas) that compose the array are at fixed locations. It is challenging, however, to implement a similar approach in the case in which the different assets are moving. If successful, SARA will provide a highly advantageous strategy to highly increase the data rate for CubeSat missions.

2. MISSION OBJECTIVES

The Solar Observing Low-frequency Array for Radio Astronomy (SOLARA) would address the significant knowledge gap in LF astronomy 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/SARA's complete mission objectives are as follows:

SOLARA:

1. Observe temporal and spatial evolution of solar weather and its interaction with Earth's magnetosphere.
2. Produce all-sky map in three bands between 30MHz and 30kHz with spatial resolution of at

least 1 arcminute.

3. Observe magnetospheric radio emissions from Jupiter, Saturn, Uranus, and Neptune with resolution of 10 arcseconds and search for planetary radio emission at the locations of known giant exoplanets.

SARA:

4. Test the feasibility of a MIMO system in the space environment.
5. Demonstrate a communication data rate of at least one order of magnitude higher than traditional (low gain) CubeSat communication systems.

3. CONCEPT OF OPERATIONS

The science goals of SOLARA require a constellation of spacecraft. Aperture synthesis imaging works only when multiple receivers at spatially separate locations are used in concert to form an image of the sky. The full SOLARA mission will be composed of a 20 6U CubeSats transported by a carrier vehicle to their final LL1 orbit.

3.1 Array delivery system

SOLARA must reach Lunar L1 (LL1) (see **Orbit/Constellation** section), so a carrier is required to transport the 6U spacecraft to their final orbit. While it is theoretically possible for the individual CubeSats to propel themselves to LL1, it would require significant fuel mass (~2 kg) for each CubeSat to reach its final orbit. Though each CubeSat is capable of carrying that much fuel, it would leave little in reserve for station keeping and array adjustment maneuvers. The long duration of the flight is most concerning due to the cumulative effects of radiation on minimally shielded spacecraft. A carrier spacecraft is a better option for three reasons: it allows the SOLARA CubeSats to conserve mass for ADCS use, it will provide some shielding from radiation damage, and it will provide backup functions for the array.

Table 1 – SOLARA/SARA timeline from launch to end of planned science operations

Event	Time
Launch to GTO	1 day
Initial check-out in GTO	< 1 week
GTO to LL1 insertion	~ 3 months
CubeSat deployment	1-2 days
Array commissioning	1-4 weeks
Science operations	1 year
Total mission	**~1.5 years**

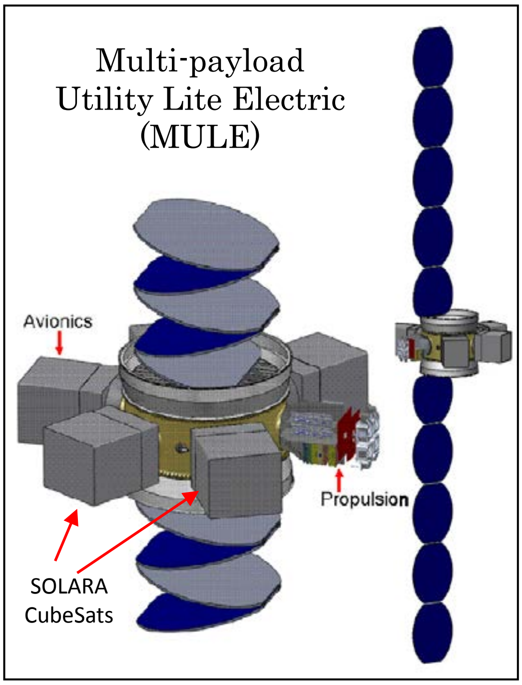

Figure 2 – The MULE carrier developed by United Launch Alliance, Comtech AeroAstro, Busek Space Propulsion and Adaptive Launch Solutions. Figure adapted from [10].

3.2 Launch

The carrier chosen for the SOLARA/SARA mission is an Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) ring. An ESPA ring is a secondary payload adapter that is routinely included in launches of Delta IV and Atlas V rockets. The ESPA ring has up to 6 circular ports around its circumference that serve as attachment points for secondary payloads weighing up to 200 kg each. The ESPA ring used for SOLARA would be equipped with an electric thruster, a set of 4 PPOD bundles to accommodate 20 6U CubeSats, a communications system, solar panels and a power management system, and an avionics subsystem for guidance, navigation, and control (GNC). The communication system will consist of a high-gain deployable dish antenna with a backup patch antenna. An FPGA-based avionics system will handle GNC, telemetry updates, and the CubeSat deployment sequence. An example of such a configuration is presented.

SOLARA will be a fully redundant system that will operate completely independent of the carrier vehicle. Each spacecraft will be identical and will be able to assume the role of any other spacecraft in the event of damage to a member of SOLARA. The SARA system will allow the SOLARA spacecraft to act as a synthetic high gain antenna to increase the data downlink rate to Earth. While previous concept studies similar to SOLARA have assumed that the carrier vehicle must act as the communications relay and central correlation station, the SOLARA system design allows complete functionality independent of the carrier, thereby eliminating a single point of failure.

Since carrier vehicle must be equipped with a propulsion system, a basic communication system, a power system, and an avionics system to accomplish its mission, it is also capable of providing backup communication and computational power for the SOLARA array once it is deployed. Though SOLARA/SARA can function completely independently of the carrier once deployed, the carrier's high gain antenna is still a useful tool for additional data downlink. SARA is an experimental technology, so a well-established backup is prudent. If necessary, the carrier avionics could take on some correlation and/or data storage functions.

3.3 Orbit transfer and constellation deployment

SOLARA's ESPA carrier will be launched to a Geostationary Transfer Orbit (GTO). Once in GTO, the ESPA carrier will perform a basic systems check-out before beginning thrusting towards LL1. The ESPA carrier will be in transit for ~3 months. See Figure 3. GTO orbits are often used by commercial communications satellites en route for geostationary orbit, allowing relatively frequent access to GTO for secondary payloads.

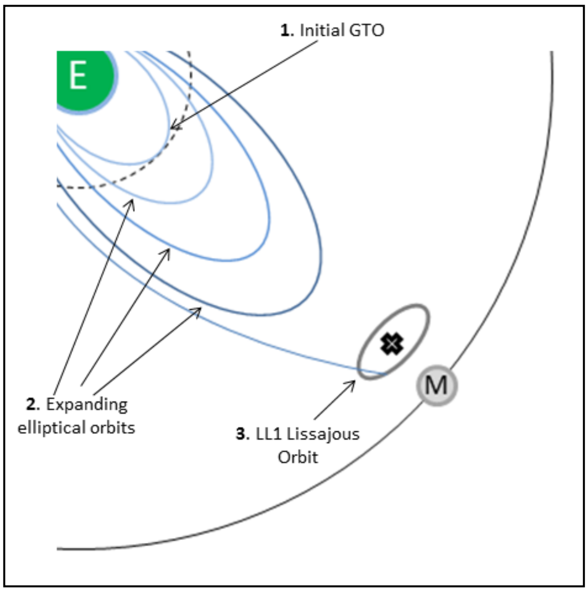

Figure 3 – Sequence of events from launch to GTO orbit to insertion into LL1 Lissajous orbit. The carrier will take many more orbits than shown to reach the LL1 insertion point.

The ESPA carrier will begin deploying the SOLARA CubeSats at safe intervals once in a stable LL1 halo orbit. Once deployed, the CubeSats will detumble and begin performing basic health checks. Each spacecraft will then deploy its solar wings and set up a very slow spin (one rotation/month) to ensure that the solar panels always face the sun. Once per day, all the SOLARA spacecraft will reorient themselves to point their S-band patch antennas at the Earth for a communication pass. After establishing a reliable power generation attitude, each unit will use its own onboard electrospray thrusters to position itself in a spherical cloud with a maximum diameter of 10 km, obeying minimum and maximum separation rules.

3.4 Commissioning

After array formation is complete, the spacecraft will complete the inter-satellite ranging and data transfer and begin data collection. During the initial check-out phase (expected to last 1-4 weeks), the carrier spacecraft will be used for data relay. SOLARA will perform broadband snapshot imaging of the sun and will relay both raw and processed data to the ground for analysis and troubleshooting.

Once the SOLARA units are performing as expected, the SARA system will be tested in three steps:

1. **Single link communication check-out**: Each individual spacecraft will communicate at low data rate to one Earth ground station. This initial test will allow the discovery of any malfunctioning spacecraft.
2. **Inter-satellite link communication check-out**: Each individual spacecraft will collect data from every other spacecraft. One at a time, each spacecraft will relay this data back to Earth. This second test will verify that the inter-satellite links are all properly working. Specifically, one spacecraft will be considered the Master of the network and it will have the main task of periodically sending the synchronization signal to the other spacecraft. If the Master malfunctions, another spacecraft will act as the new Master for the network. The Slaves will periodically send their attitude to the Master.
3. **SARA communication test**: A sequence of data will be transmitted at the same time by each of the spacecraft. The receiving ground station will collect the signal and combine them on the ground to minimize the computational requirements on-board the SOLARA spacecraft. The combined signal will be received with a quality that is significantly higher than the one that would be obtained by each spacecraft individually. Measurements of SNR received will be performed to quantify the performance of the system. Higher data rates may be attempted if prior testing is successful.

During this final stage of testing, SOLARA will also be carefully calibrated. Since SOLARA's useful frequency range extends to 30 MHz, observations will overlap slightly with ground-based arrays. This overlap will allow SOLARA to perform calibration by attempting to match sources to those identified in ground-based surveys.

3.5 Science Operations

SOLARA will begin science operations lasting for 1 year after fully testing and characterizing the science payload and SARA experiment. Initial imaging will focus on solar weather and its interaction with Earth's ionosphere. Next, SOLARA will image the solar system's giant planets to better understand the localized sources of low frequency radio emission. Finally, SOLARA will conduct an all-sky survey for bright, previously unknown low frequency sources.

During daily operations, SOLARA will communicate with the Earth once per day when the SARA patch antenna is favorably aligned with the Earth. Since SOLARA spacecraft track the sun, this contact will occur around mid-day when the "back" of the spacecraft will face the Earth. Contact will be maintained for as long as possible based on the availability of ground stations, but on average contact should last 15-30 minutes. Frequent downlink is critical because of the high data accumulation rate of the science payload. When not communicating with Earth, SOLARA will collect data by repeatedly sweeping through frequency bands and taking data in each frequency band for an integration time determined by the target. Data will be stored onboard and transmitted to other array spacecraft for correlation at the end of each frequency observation.

3.6 Extended mission

Over time, SOLARA will use onboard thrusters to expand beyond the original 10 km diameter sphere. Increasing the diameter of the array will increase the angular resolution of synthesis images (see Table 2). Previous observations will be repeated with improved resolution. The maximum expected size of the array will be 1000 km. Beyond that separation, inter-spacecraft links become weak and data transfer between spacecraft is curtailed.

Table 2 - Angular resolution achieveable at different wavelengths and different array sizes

Frequency	Wavelength	θ @ 10 km	θ @ 100 km	θ @ 1000 km	θ @ 10,000 km
30 MHz	10 m	3.4’	20.63”	2.06”	0.2”
10 MHz	30 m	10.31’	1’	6.19”	0.62”
1 MHz	300 m	1.719°	10.31’	1’	6.19”
100 kHz	3000 m	17.19°	1.719°	10.31’	1’
30 kHz	10,000 m	57.29°	5.73°	34.38’	3.43’

4. 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.

The key performance parameters for SOLARA are as follows:

1. Angular (spatial) resolution of 1 arcminute at 1 MHz and bandwidth of 10 kHz
2. Sensitivity of 1 kJy

The key performance parameters for SARA are as follows:

1. **Gain/SNR received**: This parameter will be measured at the ground station by measuring the quality (BER→ Bit Error Rate) of the combined received signal. Different data rates will be tested and the amount of messages per bit received without error will provide a measurement of the BER. BER is a direct function, for any specific modulation, of the SNR. Since all the other link analysis parameters are known, it is possible to back calculate the gain of the composed system from the SNR. The expected value of this gain is difficult to assess. However, in [11], the authors performed simulations for similar systems on Earth. From [11], it is possible to notice that the expected gain (or reduction in the required SNR) for systems of 4 elements (spacecraft) is approximately 23 dB (in case of Rayleigh attenuation) and it is 25 dB for 6 elements. If these results are confirmed by the experiment, SARA will represent a great improvement with respect to the current maximum gain for the CubeSat antennas which is approximately 6-8 dB [12] in S-Band.

2. **Data Rate**: The experiment will include tests at different data rates which will allow the measurement of the performance. The expected maximum data rate, for an orbit around LL1, is 57 Kbps.

3. **Time delay for synchronization**: This parameter refers to the frequency at which the Master CubeSat needs to relay information to the other spacecraft. Data to be transmitted are the signal clock, the starting time of the next communication window to the Earth and the localization of each spacecraft. This information must be transmitted as frequently as possible to allow corrections in the clock for all the elements of the network. Alternatively, if each CubeSat is equipped with a CSAC (Chip Scale Atomic Clock), the correction required will be less frequent, hence reducing the necessity of very fast updates. With a CSAC, an S-Band signal would be enough to synchronize the spacecraft. Localization information will be sent by each spacecraft to the Master which will then forward this information back to the slaves and it will be included in the signal sent to the ground station

5. SPACE SEGMENT DESCRIPTION

5.1 Payload

SOLARA's scientific payload consists of three major components: orthogonal dipole antennas for astronomical signal reception, low noise receivers to digitize the signals coming from the antennas, and a distributed correlator to combine data from each spacecraft into a synthesized image.

Each SOLARA spacecraft will be equipped with two 6m dipoles placed orthogonally to each other. Each dipole is formed by combining two of Northrop Grumman's STEM^{TM} JIB antenna units [13]. These JIB deployable antennas are made of BeCu tubing that is rolled flat on a drum. The antenna deploys from the JIB housing in less than 2 seconds and forms a 13 mm diameter tube. The STEM JIB antenna has flown on a variety of space missions spanning several decades and has a 100% success rate [13]. The location of the antennas on the spacecraft is shown in Figure 4 and the radiation pattern obtained from the orthogonal dipole configuration is shown in Figure 5.

The dipole antennas will be connected directly to a low noise amplifier (LNA). The LNA output will go to a specially designed receiver developed by Francois Martel of Espace and Greg Huffman of Espace and GMH Engineering. The receiver, called the Payload and Telemetry System (PTS), is FPGA-based and sized for a CubeSat. It is capable of 1 Hz frequency tuning and bandwidths from 1 kHz to 10 MHz. The current design is optimized for 100 kHz to 10 MHz, although this range can be expanded to 30 kHz to 30 MHz with minor modifications. When high-speed sampling is required, data is buffered in the PTS for later processing.

Correlation will be distributed amongst the 20 SOLARA CubeSats. An architecture for distributed correlation is described by Gunst, et. al. [14]. In this scheme, each spacecraft is assigned a frequency channel to correlate. After data acquisition, each spacecraft in the array will exchange data with every other so that each may correlate its assigned frequency channel. Data will be routed with a packet system where the packet header contains the destination spacecraft. If necessary, intermediate spacecraft can forward data from one edge of the array to another. This system is robust to the loss of one or more spacecraft. The number of computations required for correlation grows as N^2 where N is the number of array spacecraft. If a spacecraft goes offline, other spacecraft can use their new excess computational power to take over the lost spacecraft's correlation duties.

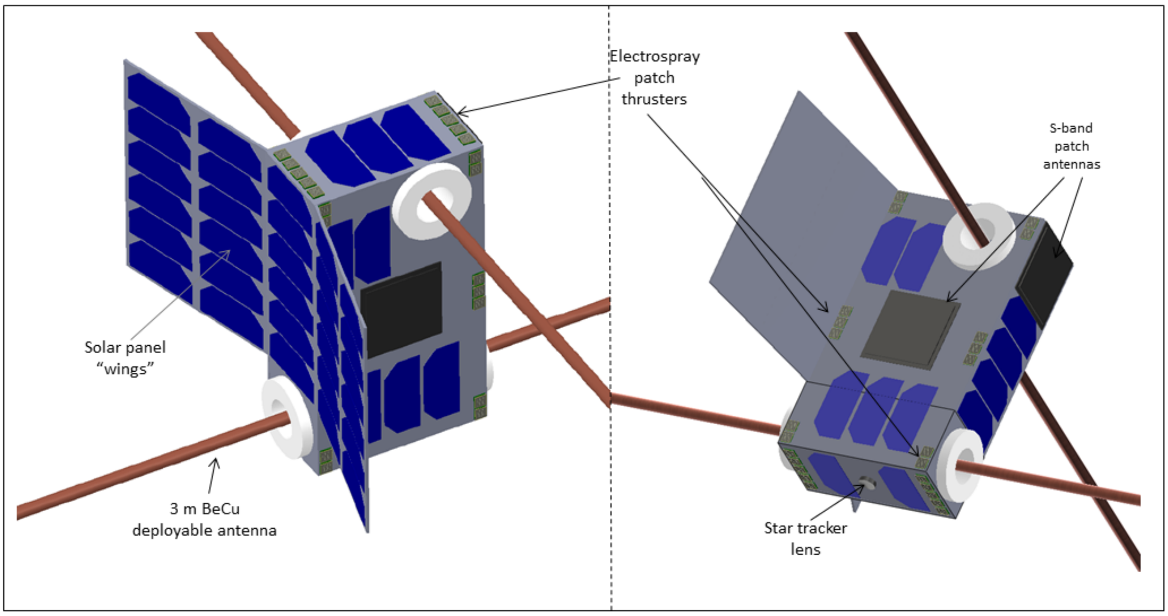

Figure 4 – SOLARA CubeSat CAD model.

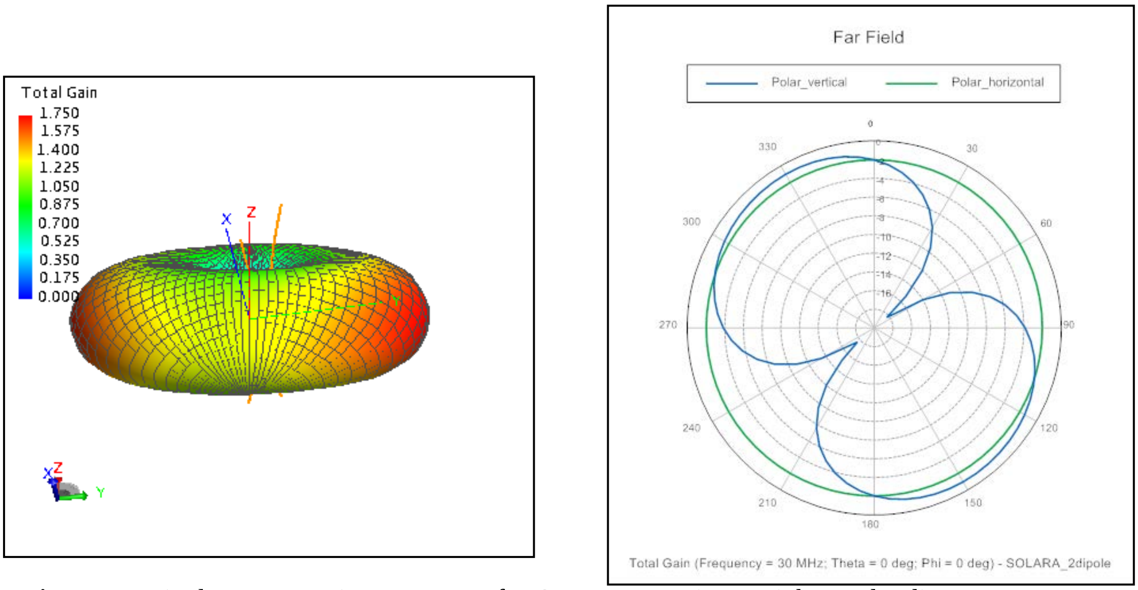

Figure 5 – Dipole antenna gain pattern. Left – 3D representation. Right – polar diagram

5.2 Communications

The SARA system includes two S-Band channels for each spacecraft. One channel is used to communicate to the Earth ground stations, while the other channel is used for inter-satellite links. Table 3 presents the link analysis computed for the cumulative link between the spacecraft and the ground station. The gain of the composed system is assumed to be 23 dB according to [11]. However, this gain could be less or more depending on the number of spacecraft and the mechanism of signal composition on the ground. Future simulations will provide a better estimation of this expected value. Deep Space Network (34 m dish) is assumed as ground station at present. It is possible to see that the system composed of multiple spacecraft can transmit in combination from LL1 at a data rate of 57 kbps with a considerable margin in both best and worst case scenario (which are determined by

Table 3 – SARA link budget

Item	Symbol	Units	SARA Downlink Worst Case	SARA Downlink Best Case	SARA Uplink Worst Case	SARA Uplink Best Case
EIRP:						
Transmitter Power	P	dBW	0.00	0.00	3.00	3.00
Transmitter Line Loss	L_l	dB	-1.00	-1.00	-1.00	-1.00
Transmit Antenna Gain (net)	G_t	dBi	20.00	20.00	55.78	55.78
Equiv. Isotropic Radiated Power	EIRP	dBW	19.00	19.00	57.78	57.78
Receive Antenna Gain:						
Frequency	f	Ghz	2.44	2.44	2.44	2.44
Receive Antenna Diameter	D_r	m	34.00	34.00		
Receive Antenna efficiency	η	n/a	0.50	0.50		
Receive Antenna Gain	G_r	dBi	55.78	55.78	20.00	20.00
Free Space Loss:						
Propagation Path Length	S	km	324,400.00	360,000.00	324,400.00	360,000.00
Free Space Loss	L_s	dB	-210.42	-211.32	-210.42	-211.32
Transmission Path and Pointing Losses:						
Transmit Antenna Pointing Loss	L_{pt}	dB	-1.00	-1.00	-0.10	-0.10
Receive Antenna Pointing Loss	L_{pr}	dB	-0.10	-0.10	-1.00	-1.00
Ionospheric Loss	L_{ion}	dB	-1.00	-1.00	-1.00	-1.00
Atmospheric Loss (H2O and O2 losse:	L_{atmo}	dB	-0.30	-0.30	-0.30	-0.30
Loss due to Rain	L_{rain}	dB	-2.00	-2.00	-2.00	-2.00
Demodulator Loss	L_{dmd}	dB	-0.15	-0.15	-0.15	-0.15
Implementation Loss		dB	-1.00	-1.00	-1.00	-1.00
Total Additional Losses		dB	-5.55	-5.55	-5.55	-5.55
Data Rate:						
Data Rate	R	bps	57,000.00	57,000.00	57,000.00	57,000.00
Data Rate	10 log(R)	dBbps	47.56	47.56	47.56	47.56
Boltzman's Constant:						
Boltzman's Constant	10 log(k)	dBW/(	-228.60	-228.60	-228.60	-228.60
System Noise Temperature:						
Antenna Noise Temperature	T_{ant}	K	100.00	100.00	340.00	340.00
Receiver Noise Temperature	T_r	K	290.00	290.00	290.00	290.00
System Noise Temperature	T_s	K	390.00	390.00	630.00	630.00
System Noise Temperature	10 log(T_s)	dBK	25.91	25.91	27.99	27.99
E_b / N_o		dB	13.94	13.03	14.86	13.95
E_b / N_o required		dB	9.60	9.60	9.60	9.60
Margin		dB	**4.34**	**3.43**	**5.26**	**4.35**

the orbit-Earth minimum and maximum separation).

A similar link analysis has been computed for each single spacecraft communication system and the Earth ground station. The gain for the antenna on board in this case is given only by the patch antenna (assumed peak gain of 6 dB). The ground station considered is still DSN. In this case the data rate is considerably lower (2.4 kbps), but still enough to accomplish the initial steps of the mission. Additionally, the link analysis for the inter-satellite links has been computed. Assuming an inter-satellite distance between 10 km and 100 km, each satellite can communicate with each other at 64 kbps.

An STK simulation has been performed to compute the coverage time. The three DSN ground stations located in Goldstone, Canberra and Madrid are considered. The results show that the coverage is almost continuous, and hence sufficient for the purpose of this mission. Given the location of the LL1 orbit, this coverage analysis is valid for ground stations anywhere on Earth (excepting the poles).

Each spacecraft will be equipped with 2 S-Band communication systems to communicate with each other and with the Earth ground stations at the same time. The patch antennas are custom-made as well as the transceiver that will be used to communicate with DSN. For the inter-satellite links a COTS transceiver will be used. In addition to these components, the avionics system of each spacecraft will need to be equipped with a CSAC.

5.3 Propulsion

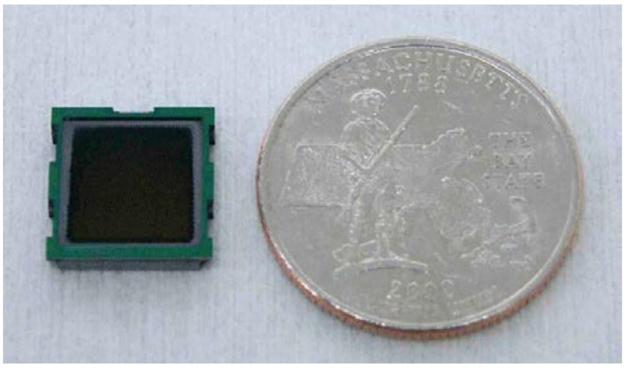

Figure 6 – Single electrspray thruster next to a quarter coin for scale.

SOLARA units will have 48 electrospray thrusters for orbit adjustment, station-keeping, and attitude control. Electrospray patch thrusters, which are in development at MIT's Space Propulsion Laboratory (SPL), are highly modular, highly efficient electric propulsion devices. They are composed of a 2D array of nanofabricated conical porous emitters covered by a high-voltage extractor grid. The fuel, EMI-BF_4, is an ionic liquid that is drawn into the porous emitters by capillarity. Once the fuel reaches the emitter tips, it is separated from the emitter by the extractor grid and accelerated away from the spacecraft at very high velocity.

These highly efficient thrusters (Isp ~3500) are uniquely suited to CubeSats because they are modular, low-mass, use non-volatile propellant, require no plumbing or pressure vessels, and operate at reasonable voltages (1-2 kV). Each thruster requires less than 1 W of power (although adding power increases thrust output). The thrusters are operated in pairs to avoid spacecraft charging. Thrusters on opposite sides of the spacecraft are fired simultaneously to generate a moment for attitude adjustment. All thrusters on one face of the spacecraft can be fired simultaneously to add velocity in a chosen direction. Though the thrust from each individual thruster is small (~100 μN), it is sufficient because there is no requirement for fast attitude or orbital maneuvers.

Fuel for the thrusters is packaged in wells directly behind each thruster. The wells are built into the back side of the panels that also hold solar cells and patch antennas. This arrangement economizes interior space and removes the need for plumbing. The EMI-BF_4 fuel has no vapor pressure, meaning that no pressure vessel is required to keep the fuel in a liquid state.

5.4 Attitude Determination and Control (ADCS)

The SOLARA ADCS system is comprised of a sensor suite and the electrospray thrusters described above. The sensor suite includes photodiode sun sensors mounted on the solar panels, gyros incorporated into the solar panels, and a star tracker for absolute position determination. While SARA's inter-spacecraft ranging can determine the relative positions and attitudes of each spacecraft within the constellation, it cannot determine the absolute orientation of the array sphere in inertial space. Star tracker measurements from multiple spacecraft will provide this missing information. Sun sensors and gyros will ensure that sun-pointing is maintained. When attitude corrections are required, the electrospray thrusters will be activated in pairs to provide the required moments.

Necessary orbit corrections will be commanded as needed from Earth. Again the electrospray thrusters will execute the appropriate maneuvers to reshape the constellation. As noted above, active formation flight is not required for SOLARA. It is sufficient to have knowledge of the baselines between each pair of spacecraft to approximately 1/10 of the observed wavelength. Active adjustment of spacecraft positions is required only if an individual spacecraft drifts far from the spherical constellation and introduces unwanted baselines. Minor orbit maintenance (30 m/s per year) will also be required for all spacecraft.

5.5 Power

SOLARA will generate power with a set of deployable solar panels that will always be pointed toward the sun. Each of the 5 panels contains 6 SpectroLab 28% efficient solar cells. These panels will generate an average of 34 W. On rare occasions when SOLARA is shadowed by the Earth or the Moon, the CubeSats will draw power from two 30 Wh batteries. Solar cells are located on all faces of the spacecraft so that power can still be generated in the unlikely event of an attitude control failure. Power management will be performed by the NanoPower unit from GomSpace.

5.6 Avionics

Essential satellite functions including ADCS control laws, communication coordination, and health monitoring of all components will be performed by a dedicated flight computer. The PTS receiver described in section 5.1 will handle all payload functions, including analog to digital conversion, correlation, and storage. Separating these computationally intensive tasks from other flight computer duties reduces the required complexity and power of the main flight computer. SOLARA will use a GomSpace NanoMind board as the main flight computer. The software running on the PTS board will be completely separated from the flight computer so that the only necessary data transfer will be commands to start or stop taking data and a data stream to be transmitted to other spacecraft and to Earth.

5.7 Structure

The structure for each of SOLARA's CubeSat components will be a customized 6U aluminum structure. Reinforced sections at the top and bottom on the structure will hold the antenna deployment units. Rails along the center of the spacecraft will hold all circuit boards. As described in section 5.3, the side panels of the spacecraft will contain fuel tanks for the thrusters. Each SOLARA unit will weigh approximately 6 kg.

5.8 Thermal

SOLARA units do not contain any components that are highly sensitive to temperature, so no active thermal control is required. The sun-facing solar panels will collect heat from the sun. The solar heat and internally generated heat will be radiated away from the spacecraft through the back and side panels that are shadowed from the sun and exposed to deep space. Thermal sensors located on critical components such as the PTS and flight computer will monitor temperatures within the spacecraft. If temperatures exceed operational limits, an attitude change will be used to adjust the position of the spacecraft and alleviate the thermal load.

6. ORBIT/CONSTELLATION DESCRIPTION

The SOLARA array will reside in a halo orbit (Lissajous) around Earth-Moon L1. This location has several benefits:

- Sufficient distance from Earth to reduce man-made radio frequency contamination (RFI)
- Uninterrupted access to the sun for power generation
- Continuous view of the Earth for communication
- Smaller distance to the Earth than LL2, allowing increased communication data rates
- Minimal station keeping required
- Easy access from initial GTO orbit

While a more distant orbit would further reduce man-made RFI from the Earth, the additional distance would require a significant reduction in data rate to close the link. SOLARA is a relatively small array with only 20 spacecraft, so its sensitivity is not likely to be limited by RFI.

Each CubeSat unit is identical and the array can function independently of the carrier vehicle once deployed. A starting array of 20 CubeSat ensures that that up to four units can be lost without significant loss of synthetic image quality. The SOLARA units will be deployed in a roughly spherical formation to ensure a diverse set of baselines. The formation may be adjusted in an open loop fashion during the commissioning phase in order to improve the quality of the synthetic image. Oberoi and Pinçon have suggested that a “cigar” shape may be more optimal for solar observations [15]. In either case, the array will be 3D, requiring

7. IMPLEMENTATION PLAN

7.1 Organization

SOLARA/SARA is in the very early stages of conceptual development, so its organizational structure is still developing. The SOLARA team is currently 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.

Partnerships with external organizations are presently being formed. A public foundation, Nexterra, has funded lab testing for a precursor mission to test the electrospray thrusters to be used on SOLARA. Also, the Defense Advanced Research Projects Agency (DARPA) is funding a Small Business Innovation Research (SBIR) project that will fly three SOLARA-like 3U CubeSats in LEO to test, among other things, the science radio receiver. These partnerships will allow the launch of precursor missions in order to reduce the risk of newly developed components. In addition to space qualifying components, the DARPA project in particular enables the testing of signal processing algorithms as well as basic formation flight controls schemes.

7.1.1 Roles and Responsibilities

MIT will be responsible for the development of SOLARA's science instruments and data processing algorithms as well as ADCS/GNC development and CubeSat bus design. Bus integration and test will be performed by an outside contractor specializing in CubeSat hardware. Carrier integration and launch will be performed by United Launch Alliance (ULA) or one of its subsidiaries. While the choice of ground station for SOLARA/SARA has not been finalized, a collaboration with NASA for use of the Deep Space Network (DSN) is being considered.

7.2 Cost

SOLARA's very early development stage makes cost estimation uncertain. Current 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 prototype SOLARA CubeSat is $1-2 million. Units produced after the precursor missions will likely cost significantly less, so a conservative estimate for the constellation of 20 satellites is $15-20 million. Launch costs, assuming the use of the MULE carrier system, will range from $10-50 million. The total cost of the SOLARA mission is roughly estimated to be $50-80 million

The SOLARA project is significantly more complex and costly than any CubeSat mission to date. While SOLARA's cost is high in comparison to single CubeSat missions, it is relatively low when compared to major observatory projects carried out by national space agencies. It is important to note that NASA and other agencies have developed concepts like SOLARA (ALFA [16], SIRA [17]), 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.

7.3 Schedule

Table 4 shows a high level schedule for SOLARA. As with cost and organization, the schedule is somewhat flexible at this stage of development.

Table 4 - Tentative schedule for SOLARA precursor missions and full constellation

Electrospray precursor mission system TVac test	Present – Dec. 2012
Science case modeling for DARPA precursor mission	Nov 2012 – May 2013
Electrospray precursor launch	Dec 2013
3U SOLARA precursor launch	Dec 2014
6U SOLARA prototype system testing	June 2015
Constellation launch	Dec 2016

7.4 Risk

The top five risks for SOLARA/SARA 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, the total cost is high for a CubeSat mission and SOLARA will require support from a major funding agency (NASA, NSF, DARPA, etc.) in order to be successful.
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*. The electrospray thruster system proposed for SOLARA relatively new and introduces some risk to the system. Significant testing will 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.

A critical component of SOLARA's development timeline and risk reduction strategy is the launch of a 1U precursor mission to test the electrospray thrusters in space.

4. *Radio Frequency Interference from Earth*. The Earth is a major noise source in radio frequencies. The Earth noise is a combination of man-made emissions and natural auroral emissions. SOLARA's location at LL1 mitigates Earth noise somewhat, but contamination from Earth is still expected to be an issue. Since the Earth is in a known position, however, SOLARA will be able to localize Earth noise and filter much of it out of the received signal.
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.

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