SOLARA/SARA:

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

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Introduction

The low frequency sky remains relatively unexplored, because low frequency radio waves (~30 MHz – 100 kHz) are reflected or severely attenuated by the Earth's ionosphere and cannot be observed from the Earth's surface. **SOLARA is an interferometric array optimized for low frequency 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.

Why CubeSats?

The availability of off-the-shelf subsystems and "piggy-back" launches significantly reduces the cost of multi-spacecraft missions.

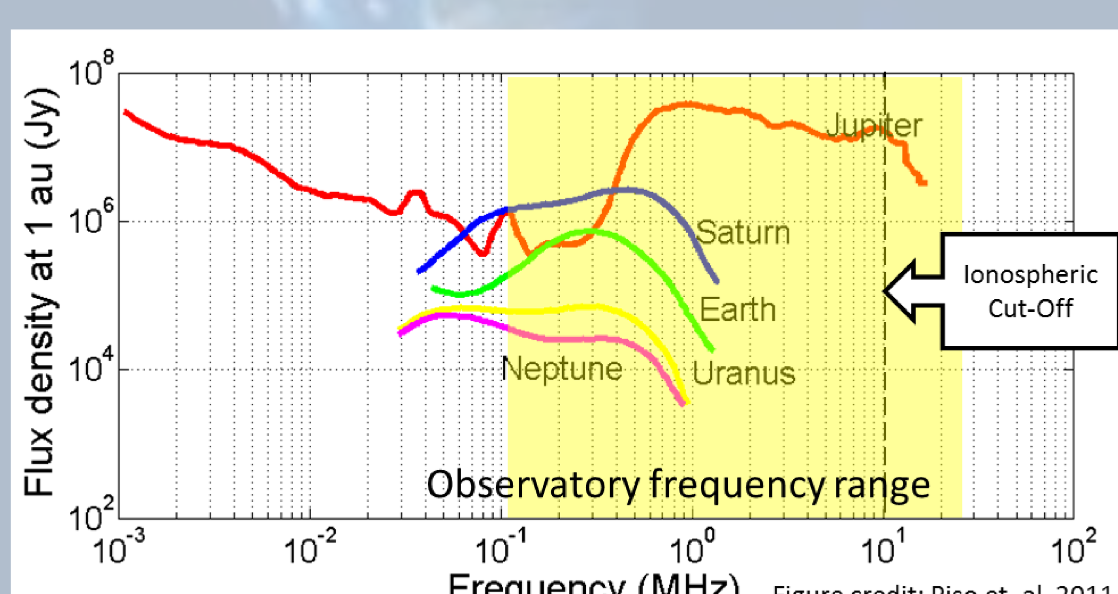


Figure credit: Piso et. al, 2011

Objectives

SOLARA's primary science goals:

- Observe temporal and spatial evolution of solar weather (particularly CMEs) and its interaction with Earth's magnetosphere.
- 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.
- Produce all-sky map in three bands between 30 MHz and 100 kHz with spatial resolution of at least 1 arcminute.

Key Parameters

- Frequency range: 100 kHz – 30 MHz
- Up to 10 MHz bandwidth
- 16-20 spacecraft (can be expanded by subsequent launches)
- Two orthogonal 6 m active dipole antennas per spacecraft
- Distributed correlation by frequency
- 35 W power
- 57 kbps downlink

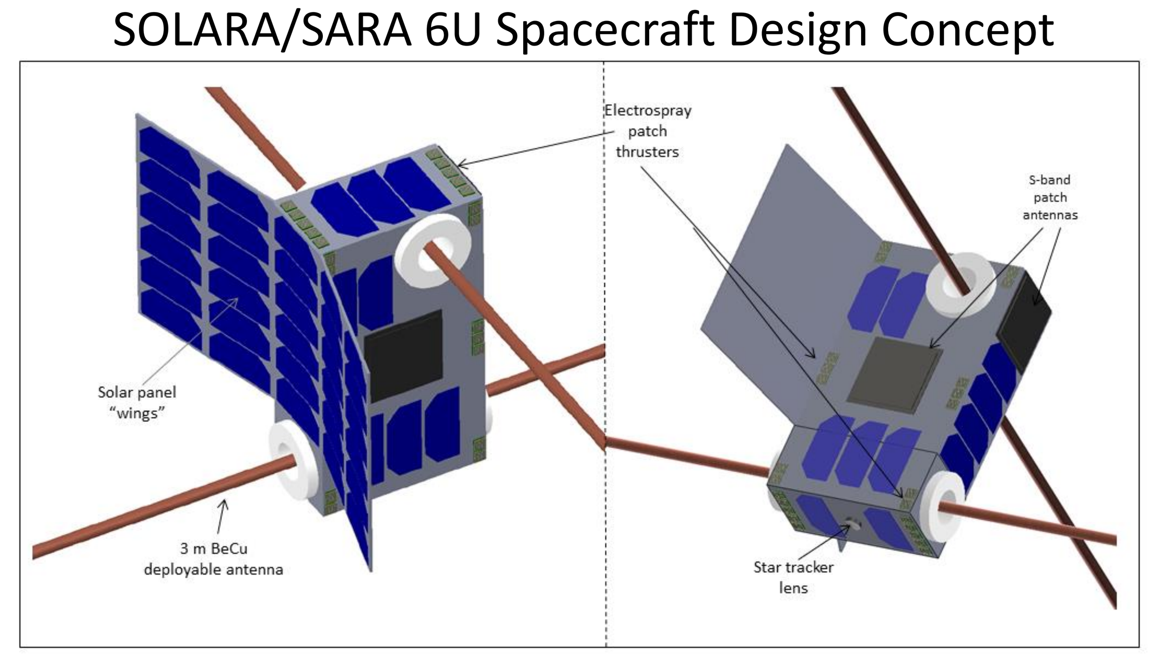
Angular Resolution:

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′

Radio Science 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 dipole is formed by combining two of Northrop Grumman's STEM^{TM} JIB antenna units. The antennas are connected to 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.

SOLARA/SARA 6U Spacecraft Design Concept

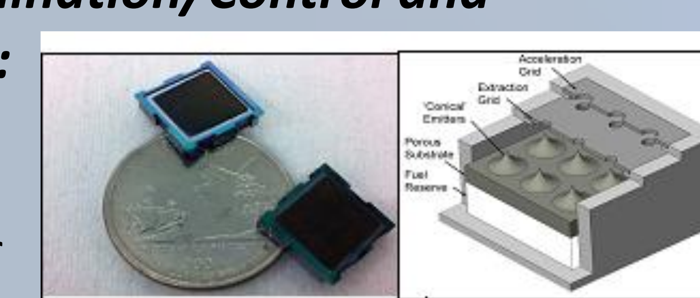


Nominal Spacecraft Design

Communication and Ranging:

The SARA system uses patch antennas attached to each SOLARA spacecraft to form a phased array. 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. SARA will use one S-band channel for inter-satellite Doppler ranging and data exchange, while the other will be used to communicate with Earth as part of a phased array. SARA will enable a data rate of ~57 kbps from LL1. Each spacecraft is also equipped with a Chip-Scale Atomic Clock for accurate time references.

Attitude Determination/Control and Station keeping:



SOLARA units will have 48 electro-spray thrusters for orbit adjustment, station-keeping, and attitude control. These highly efficient thrusters (I_{sp} ~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). The propellant is non-volatile and requires no pressure vessels or plumbing. Attitude determination is enabled by a star tracker along with multiple sun sensors and rate gyros.

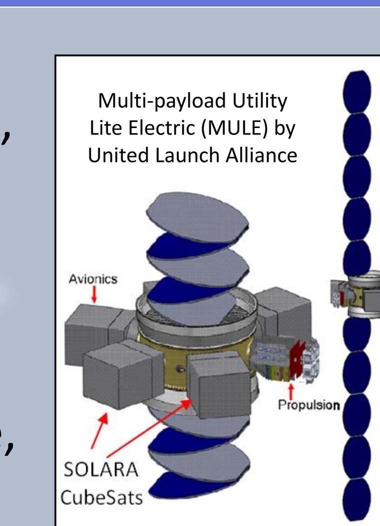
Power/Avionics:

An off-the-shelf power system along with deployed solar panels will provide ~35W. The main flight computer is an off-the-shelf microcontroller-based system. The flight computer is for high-level tasks only – computationally intensive tasks will be outsourced to dedicated subsystem processors.

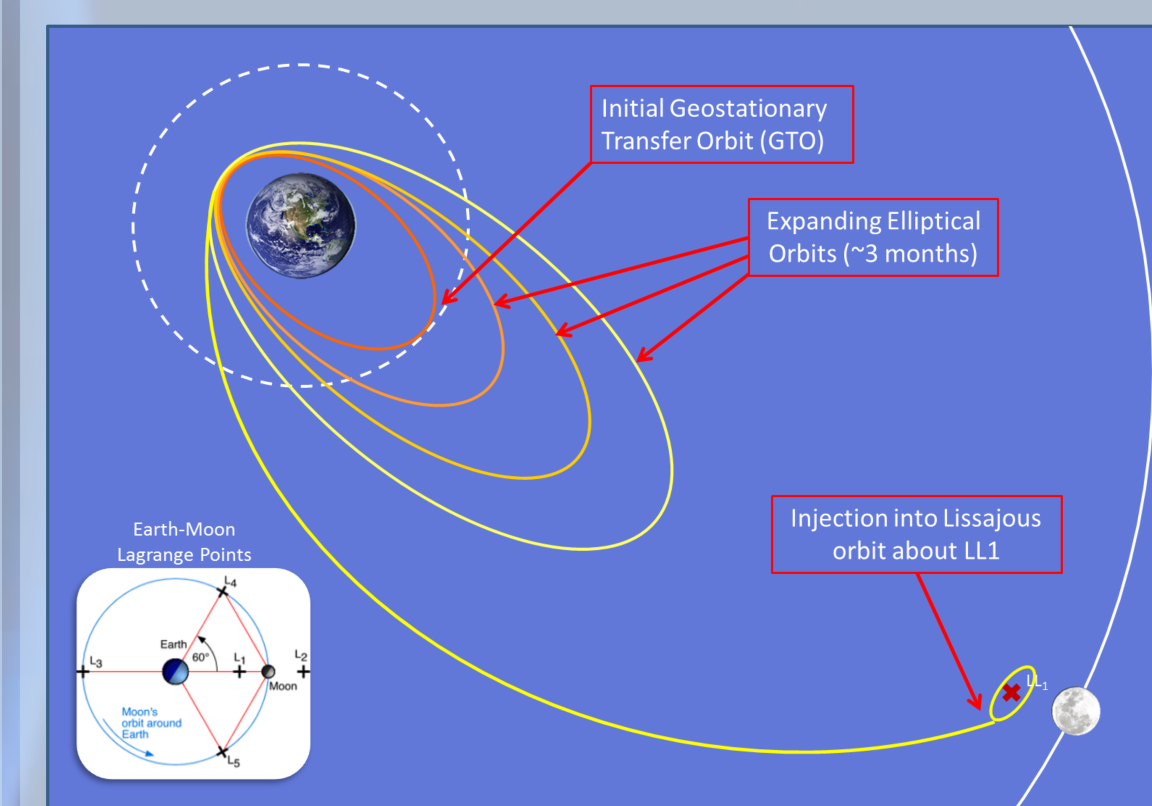
Structure and Thermal Control:

Customized 6U aluminum structure with primarily passive thermal control.

Launch and Orbit



The SOLARA CubeSats will be launched as secondary payloads, ideally into a GEO-Transfer Orbit (GTO). A carrier vehicle, such as the ESPA-ring based MULE by ULA (right), will transport the constellation to LL1. Once there, the carrier will deploy the Cube-Sats into their final locations. The 1st Earth-Moon Lagrange point (LL1) was chosen for the constellation location as a compromise between RFI, communications needs, and station keeping delta-V budget.



Future Work

SOLARA is a complex mission primarily because it requires high-performance CubeSats and formation flight far away from the Earth. Several precursor missions will demonstrate key capabilities before the full constellation is proposed.

Precursor Mission 1: Demonstrate electrospray thruster capabilities in LEO. *ETA: Summer 2014*

Precursor Mission 2: Demonstrate radio science payload and formation control with 2-3 satellites in LEO. *ETA: 2016*

SOLARA/SARA will be an example of *gradual constellation growth* –after the initial 20 CubeSats are launched, additional launches can add more CubeSats and increase the sensitivity and angular resolution of the array.

References: R. R. Weber et. al., The Radio Astronomy Explorer satellite, a low frequency observatory. *Radio Science* 6, 1085-1097 (1971); K. W. Weiler, The Promise of Long Wavelength Radio Astronomy. *Radio Astronomy at Long Wavelengths.* p.243-255. American Geophysical Union, Washington, D.C. (2000); L. Rosenqvist et. al., Extreme solar-terrestrial events of October 2003: High-latitude and Cluster observations of the large geomagnetic disturbances on 30 October. *J. of Geophysical Research* 110 (2005); A. Warmuth and G. Mann, The Application of Radio Diagnostics to the Study of Solar Drivers of Space Weather, *Lect. Notes Phys.* 656, 51-70 (2005); P. Zarka, Radio Emissions from the Planets and their Moons. *Radio Astronomy at Long Wavelengths.* p.167-178. American Geophysical Union, Washington, D.C. (2000); P. Zarka, Rasioastronomy and the Study of Exoplanets, *ASP Conference Series* 430 (2010); P. Driscoll and P. Olson, Optimal dynamos in the cores of terrestrial exoplanets: Magnetic field generation and detectability. *Icarus* 213, 12-23 (2011); J.-M. Griessmeier et. al., The Influence of stellar wind conditions on the detectability of planetary radio emissions. *Astronomy & Astrophysics* 437, 717-726 (2005), J. Szatkowski, ULA Rideshare CubeSat Missions for Lunar and Inter-Planetary Exploration. *Proc. Interplanetary CubeSat Workshop* (2012); M. T. Q. Syed, Capacity and Diversity Gains of MIMO Systems in Correlating Rician Fading Channels. Master's Thesis, King Saud University (2005).; B. Klofas et. al., A Survey of CubeSat Communication Architectures. (2008); A. W. Gunst, Distributed Correlator for Space Applications. *19th Symposium on Space Terahertz Technology* (2008), D. Oberoi and J.-L. Pinçon, A new design for a very low frequency space borne radio interferometer. *Astronomy & Astrophysics* (2008); D. Jones et. al., The Astronomical Low Frequency Array: A Proposed Explorer Mission for Radio Astronomy. *Radio Astronomy at Long Wavelengths.* p.167-178. American Geophysical Union, Washington, D.C. (2000); R. J. MacDowall et. al. Solar Imaging Radio Array (SIRA): A multi-spacecraft mission. *Proc. SPIE* 5659 (2005)