The Lagrange Communication and Advanced Realtime Space-weather (LCARS) Array

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Synopsis

We explore the need and utility of the development of an array of spacecraft deployed at the Earth-Sun Lagrange points to enable three-dimensional (3D) space weather monitoring. We show that the utilization of all five Lagrange points is possible if each of the spacecraft are instrumented with modern high-bandwidth terahertz communication systems. The spacecraft deployed at the Lagrange point opposite the Earth, L3, is fully accessible through spacecraft deployed at both L4 and L5. Additionally, the deployment of such a system provides for significant levels of communication redundancy across the entire network. This array as formulated represents humanities first steps into the development of an interplanetary communications array which we designate as the SOL-Network. The Lagrange Communication and Advanced Realtime Space-weather (LCARS) Array will be capable of providing early warning of impending space weather, continuation of fundamental and applied solar and inner heliospheric research, and deployment of network communications through the utilization of spacecraft autonomy for network and data management. By also adding variable pointing directional communication systems looking at deep space, we argue that the LCARS Array is also capable of providing significant enhancement to NASA's Deep Space Network. Finally, we discuss deployment of such systems to the Lagrange points at each of the other planets expanding the SOL-Network outward providing necessary communications as humanity takes their next steps into exploring and colonizing our home solar system.

Introduction

Detailed herein is a proposed communication and space weather array. The array is developed from the baseline concept of deploying space weather monitoring and solar observation satellites (such as combining the ACE and STEREO Mission) and enhances this system utilizing matured Terahertz (THz) communications (0.3 – 10 THz --- ~1-10+ Gb/s) technologies. This concept enables the formation of an inter-spacecraft communications network; i.e., establishing spaceborne communication arrays outside of Earth's orbit usable as the first inner solar system communications array. Additionally, the proposed array will leverage the inherent stability of the orbits in the Lagrange points of the Earth-Sun system to provide for enhancements of the existing NASA Deep Space Network (DSN Comms). This paper proposes deploying the **L**agrange **C**ommunication and **A**dvanced **R**ealtime **S**pace-weather (**LCARS**) Array into the solar system. This array will provide autonomous warnings to Earth with the purposes of protecting the significant spaceborne assets near and distant from Earth, continue the significant frontier research of the Sun and interplanetary space, and serve as an autonomous communications network between Earth and points outward into the solar system.

The LCARS Array capitalizes on the significant success of the historical and present utilization of the L1 Lagrange point [ACE – Stone 1998; SOHO – Domingo 1995; WIND – Wilson; DSCOVR – Burt 2012; etc.] as a key location for the deployment of Space Weather monitoring beacon(s). In addition, the proposed LCARS array incorporates critical aspects of the STEREO Mission [Kaiser, 2008] with its dual view of the Sun recognizing this perspective as critical in the effect study of the inner heliosphere. The LCARS Array concept places space weather beacons into orbit at each of the five Earth-Sun Lagrange points. Each spacecraft includes all necessary instrumentation for in-situ surveillance of the solar wind (interplanetary medium), energetic particles, cosmic rays, and remote observation of the Sun and inner heliosphere.

This Concept Array recognizes the critical and emergent activities required for the development of Humanities persistent presence into the solar system. This paper has been prepared in response to the ongoing National Academies Solar and Space Physics Decadal Survey's purpose to explore the needed next steps in the expansion of the NASA Heliospheric Fleet. The concepts presented herein also respond in part to NASA's desire for visionary concepts that answer the question of "What should Heliophysics look like in the year 2050" [Heliophysics 2050 Workshop, USRA 2022]. A vital and critical component of this expansion supporting future manned and unmanned missions is the development of persistent and reliable interplanetary communications as well as enhancing deep space network monitoring capabilities. For this objective, the proposed individual L2-L5 spacecraft of the LCARS Array will include a variable pointing Deep Space communications dish. The LCARS system can thus be employed as a permanent and continuous set of Deep Space Communication Relays, enhancing NASA's existing Deep Space Network. Autonomous and nearly continuous levels of monitoring of deep space assets will be provided as humanity steps further into the solar system — either through exploratory spacecraft (such as Interstellar Probe see Brandt 2022), colonization of Mars [see Etherington 2017], missions to the asteroid belt such as OSIRIS-Rex (Lauretta, 2015), and beyond. Future enhancements of this Interplanetary Communications and Monitoring Array can include utilizing Lagrange points from the other planets for the deployment of the Solar System's first Inter-Planetary Communications Network: **The SOL-Network**.

LCARS Mission Concept

Our proposed mission concept would place spacecraft at each of the five Lagrange points. Halo orbits are used at L1 and L2 and parking orbits are used at each of L3, L4, and L5, see Figure 1. Each spacecraft would include all the necessary instrumentation for in-situ observations of the Solar Wind, energetic particles, and cosmic rays. All spacecraft except that at L2 would include a full suite of remote Solar monitoring instrumentation. L2 is excluded since it does not have a direct unfettered view of the sun. The LCARS array would couple the success of such programs as the ongoing ACE Mission (deployed at L1) [Stone, 1998] and the STEREO Mission [Kaiser, 2008]. The ACE Mission has been operating for 25 years and is critical for observation of direct Earth-bound solar storms. The STEREO Mission with its dual deployed spacecraft in near-Earth orbits (slight variations in orbital parameters) provides for the mechanism to remote observe the sun in a 2D configuration. The success of both the ACE and STEREO missions is recognized throughout the Heliospheric community in their ability to identify activity on the Sun that potentially affects the Earth as high-impact science missions exploring as much as possible about the Sun and transport of emergent shocks (CME's and Solar Flares) into the interplanetary medium. The combined use of the data sets from each mission has been used to drive space weather modeling such as that at the Community Coordinated Modeling Center (CCMC) at Goddard Space Flight Center (GSFC). It then seems a reasonable transition from the loosely coupled mission concept to an array such as proposed herein that it much more tightly coupled and provides mechanisms for automated and ad-hoc data analysis.

Our proposed system would permanently park the spacecraft into Lagrange point orbital positions maintaining their relative positions for the entirety of their operational life. With identical space weather and solar instrumentation placed at L1, L3, L4, and L5, a high-resolution stereo (2D+) image of the Sun and inner heliosphere from all equatorial angles becomes possible. The most demanding engineering issue regarding deployment of spacecraft at L3 is establishing communication with Earth since there is no direct line-of-sight between Earth and L3. This in part drives the specification to include high-bandwidth communication arrays capable of networking with each other. The spacecraft at L4/L5 (identified as LCARS-4 and LCARS-5) are capable of communication with all other spacecraft in the system. Figure 1 shows the deployment of these spacecraft in the Earth-Sun system showing the location of the five Lagrange points and most importantly that the line-of-sight of LCARS-4 and LCARS-5 includes all other spacecraft (LCARS-1, LCARS-2, and LCARS-3). (Note: Sun, Earth, and Moon sizes are significantly overexaggerated in this figure).

The LCARS spacecraft would be configured with autonomous "networking" communications software managing the inter-satellite network and becoming Humanities first interplanetary communication network (SOL-Network). The purpose of also including a spacecraft at L2 (LCARS-2) is then to provide for full communications redundancy with the capability to download data from the network using either LCARS-1 and LCARS-2 or both (to increase overall bandwidth). The system envisioned is engineered with redundant communications between LCARS-1 and LCARS-2 (or L1<>L2), L4<>L5, and the critical redundancy links between L3<>L4 and L3<>L5. Earth (or Lunar) ground-based primary communication with the network is accomplished solely by communications to both LCARS-1 and LCARS- 2 spacecraft. Uploaded satellite commanding is done through network broadcast to LCARS-1 and LCARS-2 and then autonomously transmitted outward using the network to all other satellites with either network specific or spacecraft specific targeted commanding as identified by the specifics in the data stream.

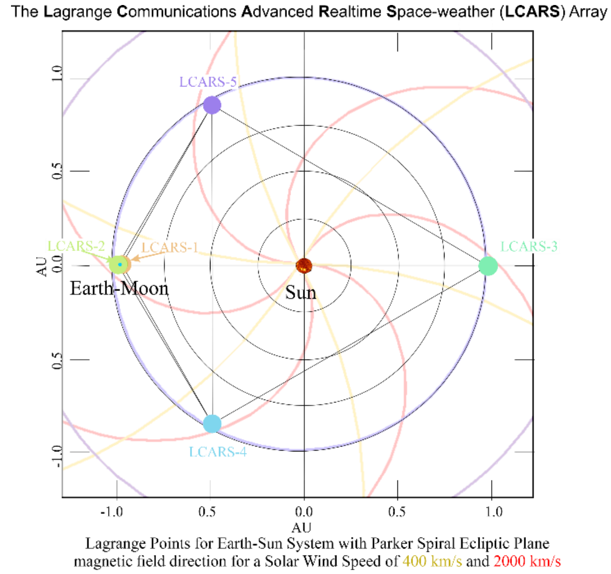

Figure 1. Deployment of the LCARS Array at each of the five Lagrange points of the Earth-Sun system.

A final aspect of this system as deployed is that the LCARS Array also has unfettered access to deep space. As part of the exploration of what might be possible (Heliophysics 2050 workshop), this white paper strongly suggests the inclusion of a Point-able Deep Space Antennae Array with the capability of providing long duration communications outward as well as continuous monitoring of deployed assets including such spacecraft as the Interstellar Probe, Voyager 1/2, New Horizon, and those missions currently being considered for deployment to Jupiter, Saturn, and Uranus. As proposed in this white paper, LCARS Deep Space Network (LCARS-DSN) would represent a significant enhancement to the existing NASA Deep Space Network not just by providing uninterrupted monitoring of the spacecraft but also by providing a redundant capability once data is received from such long-range communications.

LCARS Science Goals

1) Structure of the Solar Wind at 1 AU. (One example of many solar wind science topics)

One of the biggest mysteries (unknowns) in the solar system at this time is the processes that exist accelerating solar plasma at the photosphere (~4500 ^{O}K) to the million-degree temperature of the plasma in the corona. Complementary to this mystery is the nature of the transport of the solar wind into interplanetary space and the fine scale details of the evolution of the structure of the solar wind. Solar activity generates organized structures of plasma injected into the inner heliosphere via the solar wind through "reconnection physics" [see review article Hess and Cassak, 2020]. As the solar wind plasma and magnetic field propagates outward these various structures creating the solar wind near the top of the Corona start a process of outward transport all the while "mixing" through dissipative processes such as diffusion, turbulence, and additional reconnection physics. [Gosling et. al 2005]. As injected, the plasma and energy are very well organized but the turbulent and dissipative processes cause the energy to trickle downward into smaller scales until at the smallest scale energy is dumped into the turbulent kinetic scales that have become mixed and thermalized forming the fine structure of the observed Solar Wind at 1AU. **In considering this problem from the fundamental physics using models compared to the observations, it becomes clear that there are "chaotic" processes currently not understood nor included in existing solar wind plasma transport models.** [see discussion in Zank, 2021]

2) Coronal Acceleration Physics and Transport *(One example solar physics science topics)*

In conjunction with science goal #1 above, observation of the corona through X-Ray frequencies provides the ability to understand the transport of the million degrees+ plasma forming the solar corona. The physics behind the acceleration and outward transport during reconnection and formation of flares and CME's is poorly understood. Using an X-ray instrument onboard each of the LCARS spacecraft, the LCARS array would then have the capability of seeing each layer (defined by temperature) of the sun from the photosphere outward through the upper layers of the corona. In a similar fashion to how X-Ray Tomography is used to build 3D models of a medical specimen using 2D X-Ray slices, the multi-point satellite observations of the LCARS array will provide the capability of building a 3D model of the dynamics of the filaments of plasma for the entirety of the solar corona.

Scientific Benefit from the LCARS Array:
Utilization of an array such as the LCARS Array provides the capability of directly coupling the in-situ and remote observations to formulate a larger 3D picture of the physics driving the development of the Solar Wind and transporting energy into interplanetary space.

Network Operational Goals

1) Implement continuously operating interplanetary communications network (SOL-Network)
The SOL-Network implemented through the LCARS array would implement humanities first operational interplanetary network. The distances between each satellite will be on the order of hundreds of kilometers all the way to several astronomical units (AU). The technical complications of attempting to implement an actively and autonomous communicating network when the time delays are as high as 13-16 minutes (~800 to 1000 seconds) present the need for high bandwidth redundant communications protocols.

The autonomy of the network will be implemented such that multi-packet communications are handled through the use of AI systems working through predictive algorithms to handle communications with such large transport delays. We note that existing ethernet based TCP/IP communication protocols are fully capable of working with such large time delays and can provide a baseline for such an operational network but they would most likely not be the best set of protocols implemented on top of the underlying communications systems.

2) Implementation of a Terahertz communication system
Current communication technologies are pushing the boundaries of Terahertz signal frequencies (0.3 to 10 THz). These high frequency systems have the capability of large data transport upwards of 10 Gb/s in a fully implemented Earth based (small scale) system. Implementation of such an array in a spaceborne system will require technologies capable of maintaining coherent Terahertz signals between satellites, an aspect which has been discussed in other LCARS-related white papers [Cooper, 2022]. Once implemented the LCARS Array will be capable of transporting the significantly large amount of data between satellites and providing for high-bandwidth communications to Lunar stations and Earth orbiting communication arrays.

Humanities Benefit from the LCARS Array:

Utilization of an array such as the LCARS Array provides the capability of an autonomous communications network that can be used by future robotic and human exploratory missions and ultimately forms the beginnings of stable communications between the human expansion to Mars and beyond.

LCARS Space Weather sensors

As a concept mission the proposed spacecraft would be instrumented as if costs are not a driving issue although we fully recognize that the costs associated with the LCARS Array could become prohibitive if newer low-cost sensor alternatives are not used for these instruments. For purposes of resolving the above science questions (as well as the many more that exist and are otherwise not documented in this white paper), we provide the underlying details of the detectors that should be included in such a mission.

In-Situ instruments

In order to realize the above science goals, it is necessary to instrument the spacecraft with in-situ instrumentation in order to fulfill the science goals as well as provide as broad measurements that allow for new discoveries. One of the biggest issues is to understand the variable nature of the composition of the solar wind. Reaching back to earlier missions, such as ACE [Stone et al., 1998], Van Allen Probes [Fox and Burch, 2013], and MMS [Burch et al., 2016], it is clearly necessary to have wave and particle instrumentation capable of resolving the kinetic scale details of the particle transport in the solar wind as well as the evolution of the magnetic field along the Parker Spiral down to internal kinetic scales as the solar wind transports outward. We envision the following set of in-situ instruments:

Particles	Instrument Type	Instrument Details		
Plasma	Langmuir Probe	Thermal Plasma Distribution	SC Potential	Solar Wind Speed/Density
Low Energy Particles	Top-Hat / TOF	1 eV to 50 keV	Electrons + Ion Species Resolved (P, He, CNO, …)	4pi sr resolved + Pitch Angles
Energetic Particles	TOF + Layered Si Wafers	15 keV to 10 MeV	Electrons + Ion Species Resolved (P, He, CNO, …)	4pi sr resolved + Pitch Angles
Cosmic Rays	Layered Si Wafers	1 MeV to 1 GeV	Electrons + Ions (P, Heavies)	4pi sr resolved + Pitch Angles
EM/Waves				
Magnetic Field	Search Coil + Fluxgate	3 Axis	DC through 50kHz	
Electric Field	3D + Double-probe Sensors	3 Axis	DC through 1kHz	

Remote Solar Observatory

Target	Instrument Type	Details
Photosphere B-Field Vector	Photospheric Imager	2D-maps of Photospheric B-field vectors
Solar Disk	EUV Imager	Multispectral EUV Imager of solar disk
Corona	Coronagraph	Electron density of corona
Inner Heliosphere	Heliospheric Imager	STEREO based HI like imaging
Composition	Spectrometer	Occulted Spectrometer for composition
Corona	X-Ray Imager	Multispectral X-Ray Imaging of Corona

With the advent of terahertz communications, the idea of data-heavy instrumentation such as the Atmospheric Imaging Array (AIA) [Lemen, 2012] onboard SDO could be fielded at the Lagrange points, allowing for high resolution simultaneous observation of the entire surface of the sun which can be transmitted back to Earth immediately. A fully steerable radio dish could also be repurposed as a virtual array for ground-based radio astronomy to allow for extreme length baselines. The issue of timestamping and relativistic delays in signal arrival would complicate such a system but these are engineering problems that have been solved and can reasonably be implemented into the autonomy system of each of the LCARS spacecraft.

LCARS Communications Technology (Terahertz, IR, Optical Lazer)

The ability of terahertz communication between satellite platforms would be a major increase over modern systems. Leading X-band communications systems allow for 505 Mbps data rates (see Saito et al., 2016). Terahertz communication systems have already been demonstrated to have data rates of ~100 Gbps (see Koenig et al., 2013), an almost 200-fold increase in data rate.

Such an implementation would not be without requiring significant engineering solutions for potential pitfalls. It is unknown how a terahertz beam would behave in the nominal plasma of the solar wind, let alone any major transitory solar wind structures (i.e., interplanetary coronal mass ejections or corotating interaction regions) would likely have effects on beam coherence. Terahertz communication has also never been attempted over interplanetary distances, so the ability of the beam to remain coherent at these scales is an open question demanding an engineering solution. Another unknown would be the power requirements of such a system. Current terahertz systems are small and not designed for the use case we are suggesting. Thus, an attempt to constrain the power requirements based on current power consumption from terahertz arrays in use would likely be unreliable. Although at the same time recent work by Nagatsuma [2013] have developed small scale terahertz transmission arrays using only 90 μW photodiode emitters. This provides some encouragement that power requirements of the future would be significantly less demanding than current technologies.

Another potentially beneficial advancement in using terahertz communications would be the implementation of beam-steering technology to allow for LCARS to communicate within the network. To ensure the longevity of any space-bound platform, minimizing the number of moving parts is of utmost importance. This means the use of a mechanical steering array such as a deep space radio dish would have an increasing probability of mechanical failure as mission lifetime prolongs, and redundancies in such an array would affect an n-fold increase in build and launch costs, with n being the number of redundant systems. Redundancies in beam-steering electronics are relatively cheap by comparison. However, it is an unknown what the size of such a beam steering receiver would need to be, as such a communication system have never been attempted. Another known issue would be the divergence of a Gaussian beam as it propagates through space. Novel breakthroughs in beam-focusing methods would be necessary to minimize this divergence in the Fraunhoffer limit of the transmitter beam.

The rough idea would be to have such communication platforms situated strategically within the heliosphere so that as other missions, such as research explorers or space weather monitors, are brought online, they will be able to communicate directly with the LCARS network and transmit data along the LCARS pipeline real-time with no blackout windows, while a dedicated 'beam-home' platform in the LCARS network would communicate the data directly to Earth or Lunar ground stations using the L1<>L2 LCARS redundant system. One last benefit of using terahertz communications coupled with Lunar receivers is that there is no longer a need to consider attenuation losses due to atmospheric constituents and select data can be transmitted to Earth born communication satellites in a GEO orbit.

Conclusion

At a point in 2050 where this paper envisions full deployment, the LCARS Array would provide the human race the capability to provide high time resolution 3D space weather monitoring coupled with a robust full interplanetary communications network (SOL-Network). The instrumentation described for this system as deployed on the spacecraft is intended to provide current technology solutions but it is assumed that by the time the development of the spacecraft commences there will be higher precision, lower power cost, and more dynamic instrumentation for the in-situ and remote monitoring of the inner heliospheric space weather environment as well as for the high bandwidth communications array. By the year 2050 it is assumed that humanity has placed a first colony on the moon and have also landed personnel on Mars with the intent of staying very long durations. The LCARS Array would be a necessary step to ensure safety and security of those embarking on such missions.

This white paper for the National Academies Solar and Space Physics Decadal Survey is intended to take the value of human imagination and bind it tightly to the possibilities of the expected technologies in order to push the boundaries of humanities progress into exploring and colonizing the Sol system.

Acknowledgment

A final note regarding the acronym chosen for the array. LCARS is recognizable by many whom are familiar with Gene Rodenberry's Star Trek Universe [Whitfield and Roddenberry, 1968; and Star Trek in Wikipedia], LCARS stands for Library Computer Access/Retrieval System. As used in the Star Trek Universe TV shows and movies, LCARS is the primary method that the crews of starships interact with the autonomous computer systems used by those same starships. In using the LCARS acronym, the authors recognize the incredible vision of Gene Roddenberry by using this same acronym for humanities first interplanetary monitoring and communication array. This acronym was chosen because in the Star Trek universe, there are space born beacons and comm arrays throughout the solar system and into interstellar space. The LCARS Array envisioned in this white paper represents a first step of attempting to deploy such a critical aspect of what will become the infrastructure of future interplanetary exploration.

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