CubeSat Array for Detection of RF Emissions from Exoplanets using Inter-Satellite Optical Communicators

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Abstract—**We are presenting a CubeSat mission concept wherein a large number of small spacecraft furnished with Ultra-Long Wavelength (ULW) observation antennas is to be implemented to synthesize a large aperture for detecting ULW emissions from selected Exoplanets. The CubeSat Array for the Detection of RF Emissions from Exoplanets (CADRE) concept involves the placement of a swarm arrangement of CubeSats into small-amplitude Lissajous orbits around the Earth-Moon L2 point. In addition to the ULW receivers, each CADRE CubeSat will be furnished with a novel omnidirectional optical communicator [1] which should allow data sharing at gigabit per second data rates. In this paper we discuss the science goals, potential architecture and key technical challenges of an eventual CADRE implementation. We present the estimated interferometer specifications needed to detect Exoplanet RF emissions, CubeSat orbits and formations as well as CubeSat design considerations. Special focus is placed on the design of the mission-enabling inter-CubeSat optical crosslink which allows for fast sharing of the detected RF signals for subsequent correlation.**

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1. INTRODUCTION

Earth-based low-frequency radio telescopes, such as the LOw Frequency ARray (LOFAR) [2] and the Long Wavelength Array (LWA) [3], have been pushing the boundaries of radio astronomy throughout the last decade. Using interferometry, hundreds of relatively cheap dipole antennas can substitute impractically large dishes to achieve arcsecond-scale resolution. This approach has enabled astronomers to observe the lower regions of the frequency band between 30 and 300 MHz, advancing scientific research on the early universe, transient sources and cosmic rays to name a few examples.

One of the last hurdles to overcome in low-frequency radio astronomy is the observation of the Ultra-Long Wavelength (ULW) range above 10 meters, corresponding to frequencies below 30 MHz. This frequency domain contains signals from the early universe and cyclotron radiations originating from the magnetic fields of exoplanets. Sub-10 MHz cyclotron-maser instability (CMI) emissions are likely to be the most discernible signal from Earth-like exoplanets, and may indicate the presence of sufficient magnetic field strength to shield against space weather and sustain a habitable atmosphere [4],[5],[6]. However, interference processes such as scintillation, ionospheric refraction and solar eruptions severely distort signals from astronomical sources below 30 MHz [7]. Combined with the intense radio frequency interference (RFI) below 20 MHz due to man-made signals, this makes Earth-based astronomical observations in the ULW domain impossible [8].

This last virtually unexplored domain of radio astronomy could be observed by a radio interferometer located above the ionosphere. Spaced-based radio arrays are not a new concept: SunRISE (Sun Radio Space Imaging Experiment) is an American mission currently in formulation at JPL [9], and earlier European initiatives include DARIS, FIRST, SURO and OLFAR [10]. DARIS (Distributed Aperture Array for Radio Astronomy In Space) [11] and OLFAR (Orbiting Low Frequency Array) [12] both propose an array placed into lunar orbit. Both use CubeSats [13] that have been equipped with electrically short antennas. These CubeSats can operate as a swarm of identical array elements, or as a centrally controlled constellation where the array elements are simpler but dependent on a more complex satellite.

Even in space, the Earth can be a disruptive source of RFI for low-frequency observations. Auroral kilometric radiation (AKR), man-made interference and lightning can cause low-frequency disturbances that interfere with the detection of transients such as exoplanet signatures [7]. This RFI remains problematic until around 1.5 million kilometers away from Earth [14]. This distance is impractical for the transfer of substantial amounts of measurement data to Earth.

In the 1970's, the lunar-orbit RAE-2 satellite observed Earth-based RFI below 13.1 MHz [15]. At the lunar orbit's far side, shielding by the Moon provided 10-30 dB of interference suppression, a unique feature so close to Earth [5].

An array in lunar orbit would be shielded for only a fraction of each orbit [12]. An observatory at the surface on the Moon's far side could measure continuously, but would be extremely challenging to realize. We present the placement of a radio telescope array into a cluster of small-amplitude Lissajous orbits around the second Earth-Moon Lagrangian (L2) point.

The large number of simultaneous inter-satellite links (ISLs) needed to transfer measurement data is one of the main challenges for implementing a space-based radio interferometry

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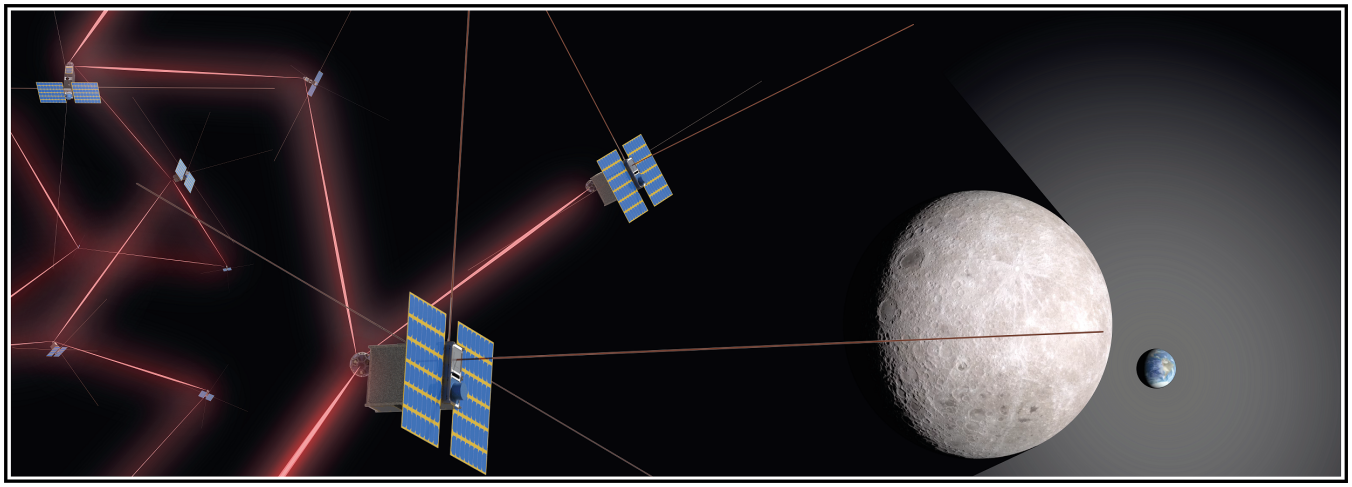

Figure 1. Artist's impression of the CADRE ultra-long wavelength radio interferometer in Earth-Moon L2 orbit, shielded from the Earth's RFI by the Moon. Omnidirectional optical communicators provide inter-satellite links.

array [7],[16],[17]. A radio frequency (RF) ISL solution for CubeSats using patch antennas has already been proposed [18], but this requires multiple antennas to achieve sufficient directivity for an ISL [19]. The subsequent power requirements become a bottleneck for scalability and the potential distances between satellites [20]. Furthermore, the unwanted large-scale introduction of man-made RF in the RFI-free zone behind the moon may impede future missions [21].

Optical communication may become an effective method for swarm communication, solving many shortcomings of RF solutions. The omnidirectional Inter-Satellite Optical Communicator (ISOC) enables simultaneous cross-link communications between multiple spacecraft at Gbit/s data rates over distances of hundreds of kilometres [1]. This mission-enabling technology would allow larger satellite networks than RF solutions could facilitate without polluting the RF measurement environment. The ISOC could also be used to provide the radio interferometer with relative positions and orientations of all array elements.

This paper presents CADRE, the CubeSat Array for Detection of RF Emissions from Exoplanets. With the Earth-Moon L2 orbit providing continuous RFI-free observation and the ISOC providing unprecedented high data rate inter-satellite communications, CADRE could enable ULW science goals and ultimately observe RF emissions from known exoplanets.

The science goals of CADRE are expanded upon in Section 2. Section 3 describes the mission architecture, and Section 4 lists the ISOC's mission-enabling applications. Section 5 describes the flight system, Section 6 lists CADRE's operational phases, and Section 7 provides concluding remarks.

2. Science Goals

Unveiling the virtually unexplored ULW domain with a space-based radio interferometer has the potential to lead to new scientific discoveries, as the observation of new frequency domains has done in the past. The processes that occur in the largest physical scales and the lowest energy levels, including the cosmological Dark Ages, the epoch of reionization (EoR), solar and planetary bursts, and exoplanet RF emissions are practically solely detectable by a low-frequency interferometer array [20].

An overview of the possible science cases, which CADRE shares with concepts such as DARIS and OLFAR, and estimations of the corresponding array requirements was made in a study by Jester and Falcke and is shown in Table 1 [5]. The table specifies the frequency range, the required spatial resolution and the resulting inteferometer baseline. Estimates of the number of antenna elements and the observation time required to achieve a 5-σ detection through aperture synthesis are given.

The large numbers of CubeSats required for the more demanding science cases, which range in the tens of thousands, are unfeasible to deploy at once. If CADRE would be realized in steps, with groups of satellites expanding the constellation each time, new science could already be possible with the first batch of CubeSats in orbit. The stepwise expansion would enable CADRE to fulfill more science objectives over time.

The predicted frequency ranges of cosmological observations, such as EoR and the Dark Ages, are just above the frequencies in the ULW domain and are observable from Earth. However, a space-based observatory could provide valuable contributions to Earth-based arrays due to the lack of ionospheric distortion.

The achievable spatial resolution in extragalactic surveys is limited to approximately one arcminute in the ULW range, due to the interstellar medium (ISM) filling our Galaxy and solar winds distorting incoming wavefronts [11]. The maximum useful baseline can be approximated with [5]

$$\text{Max. useful baseline} = 10\ \text{km} \times f_{obs}/\text{MHz} \qquad (1)$$

where f_{obs} is the observation frequency. A baseline of 100 km provides optimal resolution for observations at 10 MHz and below, which is sufficient for most science goals.

The ULW emissivity of the ISM in the Solar System's neighbourhood could be measured with only tens of antennas and a lower resolution requirement. Therefore, this science goal would be suited to the early stages of CADRE's deployment.

Cosmic ray detection is one of the most challenging galactic survey objectives. Due to the required arcsecond resolution and high sensitivity, these phenomena are better studied at higher frequencies with Earth-based telescopes [11].

Table 1. **Overview of ULW science cases for CADRE and corresponding interferometer requirements, taken from [5].**

	Frequency f [MHz]	Resolution $d\Omega$	Baselines [km]	N_{Ant}	t_{exp}(5-σ)
Cosmology					
Global Epoch of Reionization	$50-150$	$2\pi sr$	0	1	2h-20d
Global Dark Ages signal	$30-45$	$2\pi sr$	0	≥ 1	0.3-30yr
EoR 21-cm power spectrum	$50-150$	$\approx 2^\circ - 2'$	$0.05-10$	10^3-10^5	year
Dark Ages 21-cm power spectrum	$30-45$	$\approx 20' - 2'$	$1-20$	10^4-10^8	year
Extragalactic surveys	10	1'	$0.1-100$	300	2 year
Galactic surveys					
Solar System neighbourhood	$0.1-10$	degrees	$0.3-30$	$10-100$	year
Origin of cosmic rays	$0.1-30$	1"	$(3-30)\times 10^3$	10^5	100d
Ultra-High Energy particles	$10-100$	N/A	$0-5$	$1-100$	N/A (bursts)
Transients					
Solar and planetary bursts	$0.1-30$	degrees	$0.5-200$	$1-100$	min-h
Extrasolar planets	$0.5-30$	$\lesssim 1'$	$\gtrsim 35-1000$	10^4-10^{5a}	15 min

[a] N_{Ant} is driven by requiring a 5-σ burst detection within the typical burst duration of 15 min, with $t_{exp}N_{Ant} = const$.

Planetary and solar bursts are predominantly polarized and non-polarized, respectively, meaning a distinction between the two sources can be made with a suitable receiving antenna [5]. Due to the high intensity of the bursts and the low resolution required, a small number of crossed-dipole antennas is sufficient to perform observations [11]. Although the baseline requirements for obtaining spatial information of Jupiter's burst regions were considered to be unfeasible [11], the ISOC providing long-range ISL capabilities could prove to be an enabling technology.

RF emissions from magnetized exoplanets caused by the CMI can vary largely in frequency. The maximum emitted frequency is linearly dependent on the maximum magnetic field strength B_{max}, following the relation [6]

$$f_{max} = \frac{eB_{max}}{2\pi m_e} \tag{2}$$

where e and m_e are the electron charge and mass, respectively. The resulting signal is circularly polarized, and its transmission strength is related to the stellar wind velocity incident on the magnetosphere V_w , the planetary magnetic moment μ_p and the orbital distance between the star and the exoplanet A. Therefore, the expected signal strength of the received radio signal P_r can be expressed as [6]

$$P_r \propto \frac{M_*^{\frac{2}{3}} V_w^{\frac{5}{3}}}{A^{\frac{4}{3}} D^2} \tag{3}$$

where M_* is the stellar mass-loss rate and D is the distance to the observer. The radio emissions of a hot-Jupiter class planet should range in the tens of MHz with signal strengths around 1 mJy, whereas smaller exoplanets emit frequencies below 1 MHz at tens to hundreds of mJy [22]. The CMI signal strengths are less than two orders of magnitude below typical solar emissions, which is an order of 10^7 better than optical exoplanet detection [6]. Therefore, CMI emissions might be the most readily detectable signals from magnetized Jupiter- and Earth-like planets embedded in stellar wind [5]. Despite the long baselines and large number of antennas required to detect the low signal strength and achieve sufficient angular resolution, the detection of ULW emissions from exoplanets is considered the ultimate goal of CADRE.

3. MISSION ARCHITECTURE

This section expands upon the mission architecture of the CADRE radio interferometer, detailing the generated measurement data rate and the L2 Lissajous orbits.

Radio Interferometer

The CADRE constellation in L2 orbit would consist mainly of identical 6U CubeSats equipped with three orthogonal antennas, an Analog to Digital Converter (ADC), an ISOC and a low-power processor as science payload. This CubeSat configuration will be referred to as daughtership. CubeSats are a relatively cost-effective and low-complexity solution, making them a popular choice for space science missions. The identical elements simplify the expansion of the constellation over time, and enable the replacement of defective or end-of-life daughterships.

Down- and uplinks to and from Earth are managed solely by motherships, which act as central nodes in the communications network of the constellation. This limits the design complexity of the majority of CADRE's CubeSats. To facilitate this function, the science payload of a mothership differs from the daughterships. Motherships will be equipped with a more powerful optical communicator for data collection and downlink, and have more data storage and processing capabilities compared to the daughterships. To save power, the motherships may not be equipped with observation antennas and the corresponding electronics.

To establish a data link to Earth from behind the Moon, a communication relay is required as shown in Fig. 2. An estimate of the measurement and downlink data rates is provided in this section.

The placement in a small-amplitude Lissajous orbit provides the radio interferometer with a low-RFI measurement environment. However, this location also hinders direct communication with Earth, forcing CADRE to operate as a mostly independent system. The properties and technical challenges of this orbit location are expanded upon in this section.

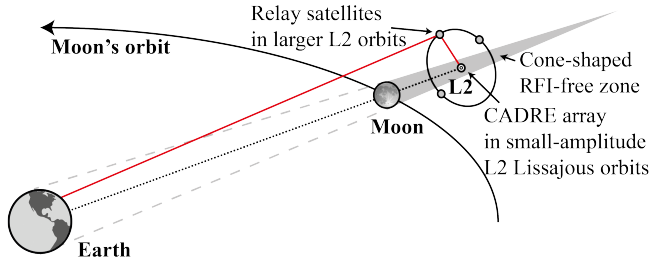

Figure 2. CADRE's L2 orbit location within the RFI-shielded cone behind the moon. Relay satellites are placed in a larger-amplitude L2 orbit.

Data Generation & Processing

The three antennas per CubeSat will be sampled with a 16-bit AD-converter at the Nyquist sample rate f_s of the full observation bandwidth below 30 MHz. A block diagram of the observation antenna electronics is shown in Fig. 3.

To reduce the required inter-satellite link capacity and processing power, only a portion of the total bandwidth is selected for observation. Limiting the instantaneous observation bandwidth Δf_{io} to 1 MHz with a polyphase filter bank would decrease the measurement data rate D_m by a factor thirty. After RFI mitigation, the total number of bits required for processing N_{bit} is reduced to 2 per antenna sample. Other concepts have proposed 1-bit samples to limit the transmitted data rate [16], but four-level processing would be more resistant to any remaining RFI. D_m would result in 12 Mbit/s per daughtership to be transmitted for processing.

The total measurement data rate is therefore

$$\begin{aligned} D_{tot} &= N \times 2\Delta f_{io} N_{ant} \\ &= N \times D_m \text{ (bit/s)}, \end{aligned} \tag{4}$$

where N is the number of daughterships and $N_{ant} = 3$ is the number of antennas per daughtership. The transmission of measurement time-stamps and location data increases the requirement for ISL capacities even further.

Radio interferometry is performed by calculating the Fourier transform of the coherence function, where the coherence function is the cross correlation between two antenna measurements averaged over an integration time T_{int} [20]. Cross correlating first and performing the Fourier transform later is known as the XF architecture, which allows the trade-off between bandwidth and spectral resolution. The FX architecture, in which cross-correlation is performed after the Fourier transform, reduces the processing requirement significantly and therefore offers better scalability [20].

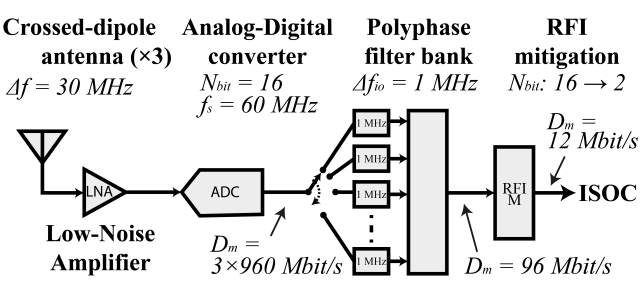

Figure 3. Block diagram of the observation antenna processing on board of CADRE's daughterships.

On-board processing may reduce the datarate of the downlink to Earth. The cross-correlated output data volume is [16]

$$D_{cor} = \frac{2(NN_{ant})^2 N_{bit} \Delta f_{io}}{T_{int} \Delta f_{res}} \text{ (bit/s)}, \tag{5}$$

where Δf_{res} is the spectral resolution of the Fourier transform. In Table 2, D_{tot} and D_{cor} are calculated for several array sizes, an Δf_{res} of 1 kHz and a typical T_{int} of 1 s.

A fully centralized processing architecture on board of a single mothership is viable as long as this mothership can receive and process D_{tot} of measurement data. When D_{tot} outgrows this requirement, the processing and uplink efforts could be distributed amongst N_M motherships. Each mothership would process a sub-band $\Delta f_{sb} = \Delta f_{io}/N_M$. The on-board processing power is not expected to be a bottleneck, so the maximum ratio $N : N_M$ would likely be determined by the ISL capabilities of the motherships.

Since D_{cor} increases quadratically with N and the D_{tot} increases linearly, on-board processing loses its merit for large array sizes. As shown in Table 2, this turning point is reached in the thousands of CubeSats. D_{cor} could be reduced by increasing T_{int} or decreasing Δf_{io} for some observations, but there exists a crossover point where the downlink of unprocessed measurement data would be more efficient than on-board processing.

L2 Lissajous Orbit

Lissajous orbits around the Earth-Moon L2 Lagrangian point have been used by the Chinese Queqiao relay satellite and two of NASA's ARTEMIS satellites [23],[24]. In both cases, the large Lissajous orbits were designed to maintain continuous line of sight with Earth. In contrast, CADRE is meant to be placed into small Lissajous orbits to stay within the RFI-shielded zone behind the moon at all times. Assuming this zone is cone-shaped, as shown in Fig. 2, the RFI-free region is approximately 1900 km in diameter at the L2 point. Since the maximum useful baseline is 300 km for an observation frequency of 30 MHz, the CADRE array centered around the L2 point would remain well within the RFI-shielded region. This is illustrated in Fig. 4.

The Lissajous orbits around L2 are quasi-periodic and unstable, so frequent small trajectory adjustments are required for station-keeping. The irregular orbits and continuous deviations from orbit could be beneficial to the interferometer, since gradually changing baselines can increase the total coverage of the u-v plane [25]. As long as collisions are avoided and the maximum baseline is kept within bounds, no exact position control or formation-keeping would be required. Rather than control, it is knowledge of the relative satellite and antenna positions that is key in space-based radio astronomy [26].

Table 2. Total generated measurement and output data and number of motherships for N array elements. Spectral resolution = 1 kHz, Integration time = 1s. D_m is based on values depicted in Fig. 3.

N	50	100	250	1000	3000	
N_M	1	1	3	10	30	
D_m	12	12	12	12	12	[Mbit/s]
D_{tot}	0.6	1.2	6	12	36	[Gbit/s]
D_{cor}	0.01	0.04	1	4	36	[Gbit/s]

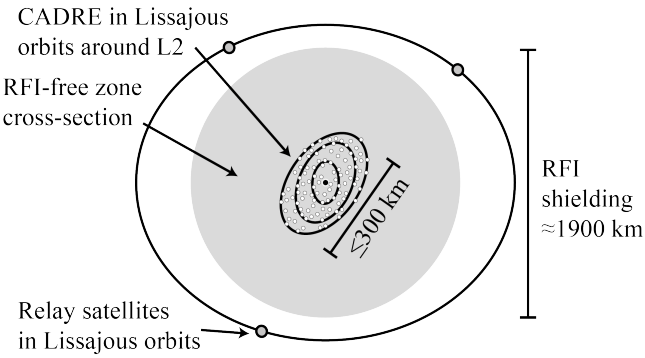

Figure 4. **Schematic of CADRE's Lissajous orbits within the cross section of the RFI-shielded zone. Not to scale.**

The exact propulsion required to enter, maintain and exit a sufficiently small-amplitude L2 Lissajous orbit is a subject for future research. The following paragraphs will only highlight the most promising strategies for orbital maneuvers and station-keeping.

Since L2 Lissajous orbits are unstable, relatively little maneuvering propulsion (ΔV) is required to insert into or depart from orbit. By placing multiple CubeSats into L2 orbit at once with a deployment mechanism, propulsion costs could be reduced further. Such a mechanism could be very similar to existing Low-Earth Orbit (LEO) deployers, but outfitted with enough propulsion to transfer to the lunar L2 orbit from a LEO or Geosynchronous Transfer Orbit (GTO). A lunar swing-by transfer trajectory from LEO, such as the trajectory used by the Qeqiao satellite, would require significantly less ΔV than a direct transfer at the cost of a longer travel time [23],[27]. The required ΔV is expected to be in the low hundreds of m/s, and 1-3 trajectory correction maneuvers are expected within the multi-day transfer duration [27].

The instability of L2 Lissajous orbits imposes the need of continuous station-keeping corrections. The required ΔV is expected to be in the tens of m/s on a yearly basis, and the time between maneuvers is expected to be in the order of days [28]. To facilitate the long-term and precise low-ΔV requirements of station-keeping corrections, Solar Electric Propulsion (SEP) using magnetically shielded Hall thrusters could be considered as a suitable option [29]. With a modest amount of propulsion on board, keeping the individual CubeSats in the constellation in orbit for several years seems feasible. The accurate absolute localization required for the correctional maneuvers could be provided by the relay satellites used for the downlink to Earth. The future Lunar Orbital Platform - Gateway (LOP-G) satellite would also be suitable due to its line of sight with both Earth and CADRE.

The disposal of CubeSats from L2 Lissajous orbit at the end of their life-time would require on-board propulsion, either from remaining station-keeping propulsion or from a dedicated Solid Rocket Propulsion (SRP) system [29]. Feasible disposal methods from an L2 orbit include a Moon impact, insertion in a heliocentric graveyard orbit and a reentry in Earth's atmosphere [30]. Considering CADRE's location, a Moon impact could be the most apparent solution as long as the risk of colliding with human assets or historically valuable lunar artifacts can be mitigated. On the other hand, insertion in a graveyard orbit might involve a lower ΔV and less complex operations due to the absence of such risks.

Number of Spacecraft

The maximum number of satellites that can coexist within the CADRE constellation is dependent on the minimum allowed range between satellites and the maximum useful baseline in the constellation. An indicative estimation can be made by assuming a planar constellation in the shape of a circle. A swarm with a diameter of 100 km, which provides optimal resolution at observations up to 10 MHz, could approximately host one hundred CubeSats that are 10 km apart from each other. Increasing the swarm diameter up to 300 km, which provides angular resolution in the order of millidegrees at 30 MHz [5], increases the number to eight hundred. A minimum range of 5 km between neighboring CubeSats would allow the constellation to host several thousands of elements.

Lowering the minimum allowed range between spacecraft increases the control effort to keep the CubeSats within their specified regions and avoid collisions, increasing the propulsion requirements and lowering the lifetime. Nevertheless, the current CADRE architecture should allow the placement of thousands of spacecraft in the RFI-free zone.

4. Optical Communication

CADRE's constellation of antenna elements is intended to grow in size and numbers over time. This forms a technical challenge for the inter-satellite transfer, processing and downlink of large amounts of measurement data. This section presents a design of an optical inter-satellite communication network that allows the fast transfer of this data.

Inter-Satellite Optical Communicator

The ISLs form one of the main challenges associated with space-based radio interferometers. In contrast to ground-based radio telescope arrays such as the LWA, a space-based array does not have the luxury of large-capacity data storage and conventional fiber optical communications to process the large amounts of measurement data [3]. A benefit of the ULW domain is the lower Nyquist sampling rate of 60 MHz, requiring lower data rates compared to ground-based arrays.

OLFAR's ISLs are realized with patch antennas located on all six sides of the CubeSats [17]. The design is based on a 50-satellite swarm: patch antennas are a simple and cheap solution for such a limited size. However, RF solutions offer too little expandability for CADRE. A constellation with thousands of CubeSats, which could be realized in the future to meet all science requirements listed in Section 2, would require so many ISLs that the RF links would be likely to interfere with each other. Moreover, the low directivity would waste energy and could impede future missions that require the low-RFI zone on the far side of the moon.

Optical inter-satellite communication is the mission-enabling technology that could solve these shortcomings. The ISOC is a spherical array of miniature transmit (Tx) optical telescopes and receive (Rx) PIN diode photodetectors providing full sky coverage, designed to fit in one CubeSat unit (U). A model of the ISOC is shown in Fig. 5 with a truncated icosacahedron geometry, with a Tx telescope on each facet and an Rx detector on each vertex [1]. A schematic depiction of the Tx optical telescope and Rx photodetector is shown in Fig. 6.

Preliminary studies have shown that a 1 W, 850 nm laser diode can provide a 1 Gbit/s cross-link data rate at distances up to 200 km with a bit error rate (BER) of 10^{-9}[1]. A

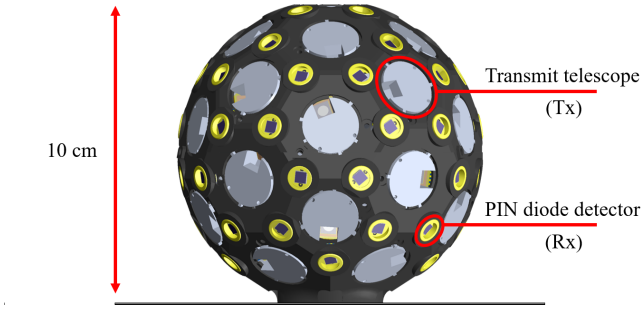

Figure 5. ISOC model with truncated icosahedron geometry [1].

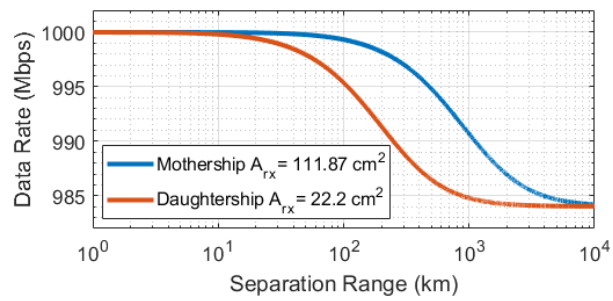

Figure 7. Maximum ISOC link data rate versus distance for a 1U (daughtership) and a 4U (mothership) ISOC, based on a shot-noise limited system [31]. Transmit power = 5 W, Allowed BER = 10^{-9}.

comparison of the ISOC and an RF solution is shown in Table 3. Taking diode efficiency and optical steering with MEMS mirrors into account, the ISOC is expected to have a similar power requirement as the patch antennas whilst delivering superior performance. The ISOC's maximum ISL capacity as function of distance, assuming a shot-noise limited pulse-position modulated system [31], is shown in Fig. 7 [32]. The data rate is limited to 1 Gbit/s by the receiver bandwith of 1000 MHz. Higher data rates at the expected ISL distances of five to ten kilometers could be achieved given developments in small-scale optical transceiver electronics.

With 20 Watts of the power budget dedicated to the ISOC, a feasible amount given modern solar panels, three simultaneous Gigabit-rate links can be sustained. Furthermore, the presence of a large number of ISOC data links will cause little or no disturbance to other ISLs and missions thanks to the high directivity of optical communication.

In order to establish an ISL, the ISOC first performs positioning and tracking (PAT). One ISOC can initialize the link by transmitting pulses of data in all directions, prompting a reply from any ISOC receiving a signal. Recent link directions could be probed first to more efficiently reacquire and track previous communication links. The receiving ISOCs will detect the pulse with multiple Rx photodetectors at different angles, allowing the angle of arrival (AoA) to be determined using a proprietary algorithm on an FPGA [1]. A targeted response will then notify the original ISOC of the presence and direction of the receiving ISOC, and allow communication to start. When two spacecraft are moving with respect to another during communication, the AoA algorithm will enable constant re-adjustments of the Tx telescopes to maintain the optical link.

Optical Communication Network

Despite the full-sky coverage of the ISOC, the CubeSat body and solar interference limit optical communication in specific directions. With sun-tracking and strategic placement of the solar panels, the blind spots caused by the CubeSat and the sun can be made to overlap continuously. Besides the known blind spots, an optical link could be interrupted unexpectedly by a third satellite crossing the communication path. Disruption Tolerant Network (DTN) applies a store-carry-forward strategy to facilitate communication in such challenging conditions, and is therefore a preferred communication strategy [33]. The relatively large buffer sizes required for this strategy can be minimized with estimations of the required data rate and the frequency of interruptions.

The ISOC requires an estimated 5W of power per 1 Gbit/s link at 200 km [1]. Given 20 Watts of available power, a single CubeSat could maintain three high-datarate links and one or two low-datarate links. For smaller arrays, such as in the early stages of CADRE, a single spacecraft could serve as the sole communication node. To limit the number of simultaneous communication links per ISOC, Time-Division Multiple Access (TDMA) could be applied to collect the data from all interferometer antennas. A central position for the mothership would be preferred to limit the ISL path lengths, minimizing BER and maximizing data rates.

A tree-shaped network structure of interconnected satellites as shown in Fig. 8 could exploit the large single-link capacity of the ISOC and limit the number of links for individual ISOCs. Most ISOCs would receive a datastream from two other CubeSats, and transfer the combined data to the next node. A single 1 Gbit/s datastream received by a mothership

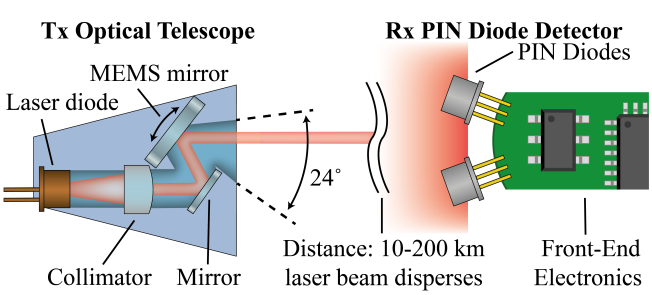

Figure 6. Schematic side view of the ISOC Tx optical telescope and Rx PIN photodiode detectors.

Table 3. Link budget comparison: RF and ISOC. Per-link performance.

Parameter	RF [17]	ISOC [1]	
Link Distance	90	200	[km]
Frequency	2.45	-	[GHz]
Bandwidth	33	1000	[MHz]
Wavelength	-	850	[nm]
Laser power	-	1	[W]
Transmitter power	4	5	[W]
Link margin	2	3	[dB]
Bit Error Rate	10^{-5}	10^{-9}	[-]
Resulting data rate	∼50	∼1000	[Mbit/s]

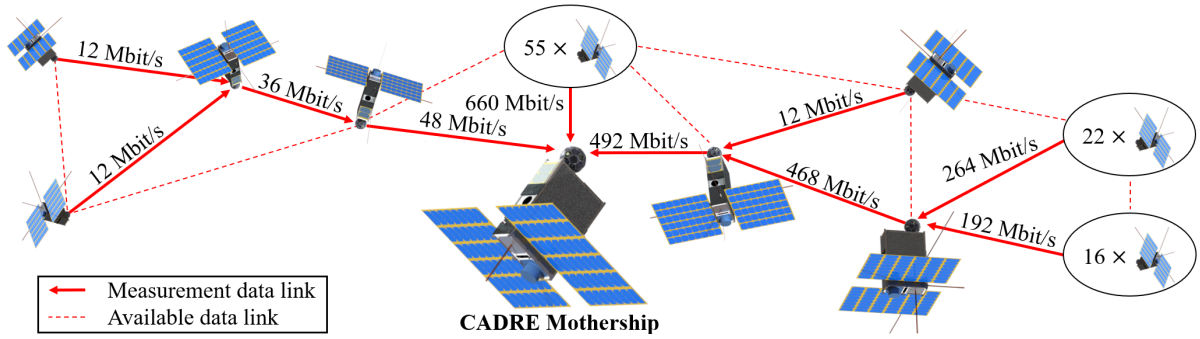

Figure 8. Simplified example of CADRE's tree-shaped ISL network with one mothership. The total transmitted measurement data (excluding time-stamp and location data) is indicated for each link.

could contain packets of data from up to 55 CubeSats with a margin of 340 Mbit/s as shown in Fig. 8. A single mothership for every hundred daughterships, as used in Table 2, allows the ISLs a margin of 1.8 Gbit/s, or 150% on top of the 1.2 Gbit/s of measurement data, to accommodate the transmission of positioning, time-stamp and location data.

The geometry of such a tree-shaped network would also decrease the average path length per ISL, decreasing the required power for a given Gbit/s link. This creates room in the power budget for more low-datarate links to improve positioning accuracy. These low-datarate links, indicated by dashed lines in Fig. 8, are useful for the DTN strategy: if an ISL becomes unavailable, an alternative path could be selected to deliver the data to the motherhips.

Downlink to Earth

The shielding effect of the Moon, whilst necessary to perform RFI-free measurements, hinders the downlink of data from the radio telescope to the Deep Space Network (DSN) on Earth. This imposes the need for a relay station, or multiple stations, to facilitate this downlink. Since CADRE's motherships would already be equipped with optical communicators, and to limit the RFI-pollution in the region shielded by the Moon, an optical downlink would be preferred.

A relay satellite in stable lunar (selenocentric) orbit would alternate communications with CADRE and Earth depending on line of sight and proximity. Due to the high cost and complexity of in-space data storage this method would require, it is unlikely to be an optimal solution. A relay station with constant line of sight to both the interferometer array and Earth could provide a direct link without the need for large data buffers. The Lunar Gateway will be located in a Near Rectilinear Halo Orbit (NRHO) around the Moon and is designed to be a communications relay station [34]. It would be well-suited as a communications relay for CADRE, although the relatively long distance to CADRE would impose a high transmission power requirement on CADRE's motherships. A relay in lunar polar orbit would have the same drawback.

The Earth-Moon L2 Lagrange point offers many larger Lissajous orbits outside of the RFI-free zone, where a satellite would constantly have line of sight with Earth. The Chinese Queqiao satellite is currently in such an L2 orbit to provide a communications relay between Earth and the far side of the Moon [23]. The relatively close proximity of this L2 orbit to CADRE, as illustrated in Fig. 2, minimizes the mothership's required transmitting power to reach the relay station.

Moon-to-Earth optical communications have been demonstrated to achieve error-free performance at data rates up to 311 Mbit/s with only 0.25 W transmitting power, and at times even at 622 Mbit/s with 0.5 W [35]. Considering the ongoing efforts on NASA's Deep Space Optical Communicator (DSOC) project [36], a reliable downlink exceeding 500 Mbit/s per relay satellite seems feasible in the near future.

The relay satellites would require an optical link with CADRE's motherships spanning at least a thousand kilometers, as illustrated in Fig. 4. A pair of dodecahedron ISOC fitted with larger-sized Rx apertures A_{rx} could achieve Gbit/s communication over longer distances as shown in Fig. 7. Constraining the downlink to 500 Mbit/s per relay satellite would make an optical link between CADRE and the relay satellite more feasible as well.

Satellite Timing and Localization

Both the time and relative locations of all interferometer element measurements must be known with sub-wavelength accuracy. For 30 MHz, this means nanosecond and sub-meter accuracies, respectively. This is significantly less stringent than the picosecond and millimeter accuracies required by ground-based arrays such as LOFAR and the LWA. Unlike the stationary ground-based systems however, CADRE is an anchorless system without access to accurate atomic clocks and the GPS-network. Therefore, satellite positioning must be achieved independently by CADRE's CubeSats without access to an absolute position or time reference.

Chip-sized Rubidium clocks such as the Microsemi Space CSAC are available that provide sufficient coherence for several minutes. Since all clocks will inevitably deviate from the true time, a synchronization method would be required to minimize relative timing differences within CADRE. This on-board clock must provide sub-picosecond jitter to facilitate the sampling of antenna measurement data at the specified 16 bits per sample [37].

The relative azimuth and elevation between pairs of CubeSats are established by the AoA algorithm. The relative distance could be determined with the ISOC's lasers and PIN diodes as well. There are several methods that could achieve this, such as a pulse-based Time of Flight (ToF) measurement [38]. Another option is to transmit a digital time-stamp rather than a pulse. If the processing time is known precisely, a receiving ISOC can determine the travel time and distance with this time-stamp and its local clock. The sub-nanosecond accuracy provided by the Rubidium clocks is sufficient to achieve centimeter-scale measurements at kilometer ranges. However, both techniques are very sensitive to relative clock drifts between the two CubeSats.

The most promising solution, a dynamic Two Way Ranging (TWR) technique that combines localization and clock synchronization using a two-way communication link, has already been developed [39]. This iterative Mobile Pairwise Least Squares (iMPLS) technique is designed specifically for element pairs in an anchorless network without access to an absolute time or position. In the case of a two-way interconnected mesh network, all clock skews and relative distances can be determined using the iterative Mobile Global Pairwise Least Squares (iMGLS) algorithm [39]. Both iMPLS and iMGLS use series of transmitted time-stamps to iteratively estimate range and clock parameters. Given the time-varying pairwise distances determined by MPLS and ISOCs, the relative positions and velocities of all CubeSats can be determined with an FPGA implementation [37].

5. Flight Hardware

This section provides an overview of the flight systems, focusing on the daughtership CubeSats with antenna elements that form the vast majority of the CADRE constellation.

CubeSat Design

The CADRE satellites would be based on the 6U CubeSat form factor, as shown in Fig. 9. CubeSats can use standardized deployment mechanisms to reduce costs and off-the-shelf components with flight heritage to reduce risk [13].

Each CubeSat would be fitted with an off-the-shelf altitude determination and control system (ADCS) such as the Blue-Canyon XACT. The electrical power system (EPS) would also consist of standard components with flight heritage, including space-rated battery cells, a control board and solar panels such as the eHawk 72W produced by MMA Design. An off-the shelf command and data handling unit (C&DH) would have to be expanded with a space-grade FPGA such as the Virtex-5QV to process measurement data and drive the ISOC subsystem. The ISOC itself would require 1.5U of space including the deployer.

Electric Power

CADRE's location around the L2 point is exposed to sunlight for the vast majority of time: the Moon eclipses the Sun once every lunar phase of 29.53 days for a total of approximately 6 hours. After deployment of the solar panels, the off-the-shelf power control board would maintain a time-averaged power-positive state to prevent excessive discharging of the batteries. During an eclipse, low-power operation would commence to prevent the batteries from draining below a safe margin.

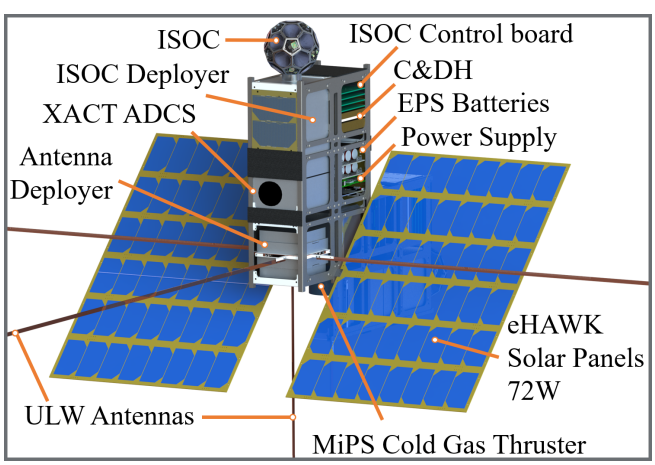

Figure 9. **Concept image of a CADRE CubeSat.**

The ADCS would use reaction wheels to counteract disturbance torques and to make the solar panels track the sun. This would maximize the generated solar power and make sure the ISOC's blind spots caused by the CubeSat body and solar interference coincide. For the latter purpose, the solar panels as shown in Fig. 9 must be turned face-down before the ULW antennas are deployed. This is depicted in Fig. 1.

Propulsion

The propulsion system pictured in Fig. 9 is the end-mounted standard Micro Propulsion System (MiPS), a cold gas thruster produced by VACCO which was used in JPL's MarCO mission [40]. A good alternative would an indium-fueled electrospray thruster as demonstrated in [41], which provided high-precision specific impulse in a compact system. This technology could also replace reaction wheels to provide high precision pointing and sun-tracking.

Depending on the ΔV requirement to exit orbit for disposal, a separate SRP could be fitted to provide a one-time boost at the CubeSat's end of life.

A lifetime-prolonging design consideration is to increase the CubeSat size to 12U. This would significantly increase an individual CubeSat's capacity for station-keeping propellant, meaning it could operate for longer without needing replacement, at the cost of larger volume, weight and costs.

Science Payload

Deployable sub-30MHz observation antennas for nano-satellites have been designed for OLFAR [18]. The design consists of three pairs of electronically coupled monopole wire antennas with a full-wavelength resonance at 30 MHz and a half-wavelength resonance at 15 MHz. To deploy the rigid 5 m monopole antennas from a CubeSat, the copper wire is enclosed with a triangular rollable and collapsible (TRAC) cross section that is invisible to RF [42].

The SunRISE mission concept, which observes a similar frequency range, proposes to use pairs of electrically short monopole antennas. Their length is approximately half the length of the first design, at 2.5 m per dipole [26]. This design uses Spiral Tube Actuator for Controlled Extension / Retraction (STACER) elements to deploy the long antennas.

In Fig. 9, a design with four identical monopoles is shown. Two monopoles are electronically connected to form a pseudo-dipole, whilst the other two monopoles are oriented in the orthogonal axes. This three-axis orientation would enable CADRE to detect the circularly-polarized RF emissions from exoplanets from any orientation. The trade-off between the length and deployment options can be made by realizing, testing and comparing the different designs.

Besides the antenna's front-end electronics (FEE), AD-converter and polyphase filter bank, an FPGA would be installed to perform the RFI mitigation. Besides transmitting the CubeSat's own measurement data, the ISOC would allow each CubeSat to relay data streams from two other daughterships to a third one. An additional 5W could be dedicated to low-data rate links with neighboring CubeSats to avoid collisions. An installed compact rubidium atomic clock would provide timing for the measurements and localization.

Motherships

As described in Section 3, the main purpose of the mothership would be to collect and process all measurement data before the downlink to Earth. Motherships may not be equipped with ULW receivers to dedicate power to these main tasks. A larger amount of station-keeping propellant would be included to provide an extended lifetime since motherships are more specialized and less replaceable than the daughterships. A 12U form factor would facilitate the extended lifetime better than the 6U volume used for the daughterships.

Although the motherships could be equipped with the same ISOC as the daughterships, it is possible to use a dodecahedron-shaped ISOC with larger Rx apertures. This would allow the mothership to receive higher datarates.

CADRE's output datarate would be in the order of several Mbit/s at the early phases of the array. Over a link distance of 1000 kilometers, an ISOC could be capable of communicating at these data rates [1]. However, the quadratic relation in Equation 5 imposes the requirement of a dedicated high-power optical transmitter for larger array sizes.

Relay Satellites

The relay satellites in larger L2 orbit would only facilitate the communication between Earth and CADRE's motherships. A large-aperture optical receiver and high-power Tx telescope would be fitted to communicate with CADRE's motherships. The downlink to Earth could be established by a similar system as demonstrated in [35], which has already achieved reliable downlink rates of 311 Mbit/s from lunar orbit.

6. Operational Phases

The CADRE mission concept can be divided in four operational phases, which are listed in further detail in this section.

Preliminary missions

Several precursor missions are expected to take place before the development on the definitive CADRE mission can fully begin. The three main goals of these preliminary missions would be to confirm the feasibility of a small-amplitude Lissajous orbit at Earth-Moon L2, to fully map the RFI below 30 MHz in this location, and to test the CubeSat hardware. One example is the Q4 mission concept, which is expected to demonstrate the multi-link capability of the ISOC [43]. Lessons learned from the preliminary missions could help improve the development and procedures for the large-volume manufacturing of CADRE daughterships, thereby reducing costs and risks. A similar roadmap has already been developed for the OLFAR project [44].

A pre-existing satellite in Lunar or Earth-Moon L2 orbit could be used to relay communications and telemetry data between Earth and the precursor missions. Alternatively, an optical downlink satellite could be deployed as a separate precursor mission to test its capabilities for CADRE. The deployment of such a relay satellite during the preliminary phase could aid the deployment of the first CADRE satellites.

Launch & Deployment in L2 orbit

The high demand for small-satellite launches has incentivized the development of methods to deploy multiple CubeSats simultaneously. Deployment mechanisms such as the SHERPA system fit tens of 6U CubeSats at once, and can be launched

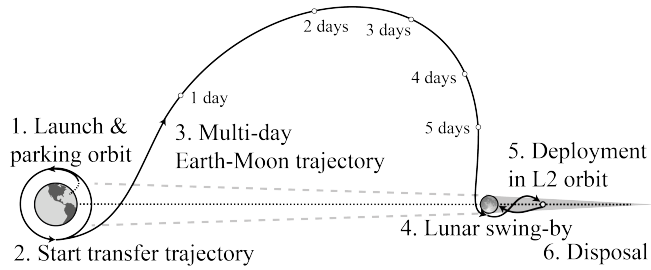

Figure 10. Schematic depiction of CADRE's operational phases, from launch to disposal. The duration of the trajectory is an estimate based on [27]

as a secondary payload to reduce costs [45]. A dedicated launch to simultaneously deploy CADRE's first mothership and around two dozen daughterships would enable science operations to start soon after deployment. CADRE's expansion missions are likely to be launched as secondary payloads.

After launch, the CubeSat deployment vehicle would transition from a parking orbit in LEO or GTO to a lunar swing-by trajectory shown in Fig. 10. This three-impulse transfer can take on the order of ten days, but requires significantly less ΔV compared to the direct transfer from an Earth parking orbit to the small-amplitude Lissajous L2 orbit. Once the nominal Lissajous orbit has been reached, the CADRE satellites would be deployed using real-time ground commands transmitted via relay satellites in Lunar or L2 orbit.

Each CADRE CubeSat would power up shortly after deployment to deploy the solar arrays. The ADCS would stop any induced rotation and point the solar panels towards the Sun to achieve a power-positive state. After successful sun-tracking initialization, the ISOCs would create the optical network and determine all relative CubeSat positions. The motherships would make contact with Earth via relay satellites, and start exchanging telemetry data and positioning instructions. Test measurements would be down-linked to Earth after antenna deployment to verify no damage occurred during launch or transit. When this is completed, the CubeSats would be directed by the mothership to maneuver towards their respective orbital positions. With all CADRE elements in position, the new science operations would begin.

Science Operations & Expansion

As explained in Section 2, few antennas are required for CADRE to start performing novel scientific observations in the ULW domain from an RFI-free region in space. An initial constellation of twenty to thirty CubeSats within a region of tens of kilometers may detect ULW signals from the Dark Ages, the ISM in the neighborhood of the Solar System and Solar and Planetary bursts with low Earth-based RFI.

Similar to the incremental deployment of large ground-based telescopes such as the LWA and LOFAR, CADRE is intended to be expanded gradually from tens to hundreds, and eventually thousands, of array elements. An example deployment schedule is shown in Fig. 11. Except for being launched as a secondary payload, the additional CubeSats would reach the Lissajous orbit at L2 in the same way as the initial group of satellites. The CubeSats could be deployed near the center of the constellation, whilst older daughterships would allow their orbital amplitude to increase naturally to create room. Expansion missions could also replace defective or end-of-life CubeSats. After an estimated ten years, limited by

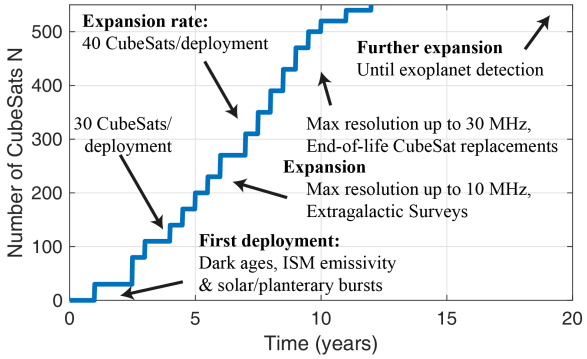

Figure 11. **CADRE's estimated deployment schedule.**

station-keeping propellant capacity, this would start to slow down the expansion as shown in Fig. 11.

After just one or two expansions using large-capacity deployers, CADRE could number over a hundred CubeSat elements and span a hundred kilometers in diameter. According to the estimates in Table 1, this would meet the requirements to measure sub-10MHz emissions from the Solar System and its neighborhood at the maximum resolution possible. Increasing the number of CubeSats to the multiple hundreds would enable extragalactic surveys at 10 MHz at this optimal resolution. According to the estimates in Table 1, such a survey could take several years.

A steady increase in CADRE's CubeSat elements would increase the resolution and sensitivity of the radio telescope, which may lead to new discoveries in several of the previously described science domains. The long-range optical communication supplied by the ISOC would allow the number of elements and the maximum baseline to be increased further than RF solutions could. In later stages of CADRE's expansion, a baseline of 300 km would enable the maximum resolution at frequencies up to 30 MHz.

When the number of CubeSats is in the low thousands, long-duration bursts in the order of hours may already be detectable from some exoplanets. These initial observations would pave the way for the last expansions, which could result in the effective detection of exoplanet emissions.

The completion of CADRE's expansion is expected to take years, perhaps even decades, after the placement of the initial constellation in L2 orbit. In this period, developments in the production process of CADRE's CubeSats and the simultaneous deployment of multiple satellites are expected to decreases the costs and increase the rate of deployment.

Decommissioning

To prevent the large-scale introduction of space debris within the Lunar sphere of influence, end-of-life daughterships running low on propulsion must be safely disposed of. This reduces the efforts of collision avoidance for other satellites within the CADRE constellation. As described in Section 3, the most likely disposal methods are lunar impact or transfer to a graveyard orbit. Both methods require an amount of leftover propulsion, although the precise ΔV for a safe disposal requires further research.

Since the disposal process could take months, the CubeSats should remain operational in a low-power mode to avoid collisions with nearby CubeSats and to maintain the disposal trajectory. If a CubeSat is unable to change its trajectory, the natural dispersion of the L2 Lissajous orbit would help it drift away from its nominal orbit. This reduces the risk of defective CubeSats interfering with the CADRE constellation.

7. Conclusion

In this paper we have presented the mission concept for CADRE, the CubeSat Array for Detection of RF Emissions from Exoplanets. Although the detection of exoplanets requires a large number of CubeSat-mounted antennas, this is not the only novel science case in the ultra-long wavelength spectrum below 30 MHz that could be unveiled by a space-based radio interferometer array within the RFI-shielded zone behind the Moon. CADRE could be gradually expanded to realize important science goals over time, with the observation of CMI emissions from known exoplanets being the mission's ultimate goal.

CADRE is presented as an interferometer array consisting of hundreds to thousands of antennas. To reduce the complexity of most CubeSats in the array, the processing and downlink would be performed by motherships. The motherships would process the measurement data on-board to reduce the volume of data to be transferred to Earth.

The exact orbit-insertion and station-keeping requirements for a small-amplitude Lissajous orbit around the Earth-Moon L2 Lagrangian point are a topic for further research. The RFI-shielding at this location would benefit the observations, although CADRE would be an anchorless network without direct access to absolute location or time references. To remedy this, dynamic two-way ranging techniques with the ISOC's transceivers would be applied to obtain relative positioning and synchronize the on-board atomic clocks.

Relay satellites in larger-amplitude L2 orbit or the Lunar Gateway would connect the motherships to the Deep Space Network on Earth to provide station-keeping information and measurement instructions. The relay satellites would be equipped with optical communicators to downlink the measurement data to Earth.

The omnidirectional Inter-Satellite Optical Communicator is the most significant mission-enabling technology for CADRE. The ability to maintain multiple simultaneous Gbit/s inter-satellite communication links would enable CADRE to grow to a larger number and size than an RF solution could, without polluting the RFI-shielded zone.

Each CADRE CubeSat would consist of off-the-shelf subsystems with flight heritage to limit costs and risk. Two designs for CubeSat-mounted deployable ULW antennas have already been proposed by other approaches, the optimal solution should be determined by testing the realized designs.

After preliminary small missions to map the RFI environment of a small-amplitude Lissajous orbit behind the Moon, the first deployment of CADRE satellites around L2 would already be sufficient to start science operations. From this point on, CADRE's capabilities would be expanded continuously by deploying additional CubeSats. With the continuous RFI-free observation provided by the Earth-Moon L2 orbit, and with the high-speed optical inter-satellite communication network provided by the ISOCs, CADRE could ultimately observe RF emissions from exoplanets.

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REFERENCES

[1] J. E. Velazco, "Omnidirectional Optical Communicator," *2019 IEEE Aerospace Conference*, March 2019.

[2] A. W. Gunst and M. J. Bentum, "The LOFAR phased array telescope system," *IEEE International Symposium on Phased Array Systems and Technology*, no. 1, pp. 632–639, 2010.

[3] S. W. Ellingson, T. E. Clarke, A. Cohen, J. Craig, N. E. Kassim, Y. Pihlstrom, L. J. Rickard, and G. B. Taylor, "The long wavelength array," *Proceedings of the IEEE*, vol. 97, no. 8, pp. 1421–1430, Aug 2009.

[4] J.-M. Grießmeier, P. Zarka, and J. N. Girard, "Observation of planetary radio emissions using large arrays," *Radio Science*, vol. 46, no. 5, 2011. [Online]. Available: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2011RS004752

[5] S. Jester and H. Falcke, "Science with a lunar low-frequency array: From the dark ages of the Universe to nearby exoplanets," *New Astronomy Reviews*, vol. 53, no. 1-2, pp. 1–26, 2009. [Online]. Available: http://dx.doi.org/10.1016/j.newar.2009.02.001

[6] M. J. Bentum, "Algorithms for direct radio detections of exoplanets in the neighbourhood of radiating host stars," *IEEE Aerospace Conference Proceedings*, vol. 2018-March, pp. 1–7, 2018.

[7] M. Bentum, C. Verhoeven, A. J. Boonstra, A. J. van der Veen, and E. K. A. Gill, "A novel astronomical application for formation flying small satellites," *International Astronautical Congress (IAC)*, vol. 3, 2009.

[8] M. J. Bentum and A. J. Boonstra, "Low frequency astronomy - The challenge in a crowded RFI environment," *2011 30th URSI General Assembly and Scientific Symposium, URSIGASS 2011*, no. 1, pp. 1–4, 2011.

[9] T. Lazio *et al.*, "The sun radio space imaging experiment (SunRISE)," *2017 32nd General Assembly and Scientific Symposium of the International Union of Radio Science, URSI GASS 2017*, Aug 2017.

[10] M. J. Bentum, A. J. Boonstra, and W. Baan, "Space-based ultra-long wavelength radio astronomy - An overview of today's initiatives," *2011 30th URSI General Assembly and Scientific Symposium, URSIGASS 2011*, pp. 1–4, 2011.

[11] A. Boonstra, N. Saks, M. Bentum, K. van 't Klooster, and H. Falcke, "DARIS, a low-frequency distributed aperture array for radio astronomy in space," *61st International Astronautical Congress, Prague*, 2010.

[12] S. Engelen, C. Verhoeven, and M. Bentum, "Olfar, a Radio Telescope Based on Nano-Satellites in Moon Orbit," *Annual AIAA/USU Conference on Small Satellites*, no. 3, pp. SSC10–III–6, 2010.

[13] R. Nugent, A. Chin, R. Coelho, R. Munakata, and J. Puig-Suari, "The CubeSat: The Pico-Satellite Standard for Research and Education," *AIAA SPACE 2008 Conference*, 2008.

[14] M. J. Bentum, A. J. Boonstra, W. Horlings, and P. van Vugt, "The radio environment for a space-based low-frequency radio astronomy instrument," in *2019 IEEE Aerospace Conference*, March 2019, pp. 1–7.

[15] J. Alexander, M. Kaiser, F. Novaco, F. Grena, and R. Weber, "Scientific Instrumentation of the Radio-Astronomy-Explorer-2 Satellite," *Astron. & Astrophys.*, vol. 40, no. 4, pp. 365–371, 1975.

[16] R. T. Rajan, S. Engelen, M. Bentum, and C. Verhoeven, "Orbiting low frequency array for radio astronomy," *IEEE Aerospace Conference Proceedings*, 2011.

[17] A. Budianu, T. J. Castro, A. Meijerink, and M. J. Bentum, "Inter-satellite links for cubesats," *IEEE Aerospace Conference Proceedings*, pp. 1–10, 2013.

[18] A. Budianu, A. Meijerink, M. J. Bentum, D. M. Smith, and A. J. Boonstra, "Antenna architecture of a nano-satellite for Radio Astronomy," *IEEE Aerospace Conference Proceedings*, pp. 1–10, 2014.

[19] K. A. Quillien, S. Engelen, and E. K. A. Gill, "Astronomical antenna for a space-based low frequency radio telescope," *27th Annual AIAA/USU Conference on Small Satellites*, 2013.

[20] R. T. Rajan, A. J. Boonstra, M. Bentum, M. Klein-Wolt, F. Belien, M. Arts, N. Saks, and A. J. van der Veen, "Space-based aperture array for ultra-long wavelength radio astronomy," *Experimental Astronomy*, vol. 41, no. 1-2, pp. 271–306, 2016.

[21] C. Maccone, "Nasa gateways at l1 and l2 and the radio-quiet moon farside imperative," *Acta Astronautica*, vol. 57, pp. 145–155, Jun 2005.

[22] T. J. Lazio, W., W. M. Farrell, J. Dietrick, E. Greenlees, E. Hogan, C. Jones, and L. A. Hennig, "The Radiometric Bode's Law and Extrasolar Planets," *The Astrophysics Journal*, vol. 612, pp. 511–518, Sep. 2004.

[23] Y.-x. Gao, Y.-m. Ge, L.-x. Ma, Y.-q. Hu, and Y.-x. Chen, "Optimization design of configuration and layout for queqiao relay satellite," *Advances in Astronautics Science and Technology*, Jun 2019. [Online]. Available: https://doi.org/10.1007/s42423-019-00034-0

[24] M. Woodard, D. Folta, and D. Woodfork, "ARTEMIS: The First Mission to the Lunar Libration Orbits," in *Proceedings of the 21st International Symposium on Space Flight Dynamics*, 2009.

[25] K. Belov *et al.*, "A space-based decametric wavelength radio telescope concept," *Experimental Astronomy*, vol. 46, no. 2, pp. 241–284, 2018.

[26] J. Kasper, J. Lazio, A. Romero-Wolf, J. Lux, and T. Neilsen, "The Sun Radio Interferometer Space Experiment (SunRISE) Mission Concept," *2019 IEEE Aerospace Conference*, pp. 1–11, 2019.

[27] R. W. Farquhar, "The utilization of halo orbits in advanced lunar operations," Tech. Rep. NASA TN D-6365, 1971.

[28] D. Folta and F. Vaughn, "A survey of earth-moon libration orbits: Stationkeeping strategies and intra-orbit transfers," in *AIAA/AAS Astrodynamics Specialist Conference and Exhibit*, 2014. [Online]. Available: https://arc.aiaa.org/doi/abs/10.2514/6.2004-4741

[29] A. R. Tummala and A. Dutta, "An overview of

cube-satellite propulsion technologies and trends," *Aerospace*, vol. 4, no. 4, 2017. [Online]. Available: https://www.mdpi.com/2226-4310/4/4/58

[30] R. Armellin, P. Di Lizia, G. Di Mauro, M. Rasotto, and M. Landgraf, "Disposal strategies for spacecraft in lagrangian point orbits," in *24th AAS/AIAA Space Flight Mechanics Meeting*, Feb 2014.

[31] B. Moision and H. Xie, "An Approximate Link Equation for the Direct-Detected Optical PPM Link," *Interplanetary Network Progress Report*, vol. 199, no. 27, pp. 1–14, Nov. 2014. [Online]. Available: https://ipnpr.jpl.nasa.gov/progress_report/42-199/199A.pdf

[32] A. C. Aguilar, J. E. Velazco, and K. Cahoy, "Simultaneous Optical Links with the Inter-Satellite Omnidirectional Optical Communicator," in *IEEE Aerospace Conference Proceedings*, Mar 2020.

[33] Khabbaz, Maurice and Assi, Chadi and Fawaz, W, "Disruption-Tolerant Networking: A Comprehensive Survey on Recent Developments and Persisting Challenges," *Communications Surveys & Tutorials, IEEE*, vol. 14, pp. 1 – 34, Jan 2012.

[34] T. Cichan, S. A. Bailey, A. Burch, and N. W. Kirby, "Concept for a crewed lunar lander operating from the lunar orbiting platform - gateway," in *69th International Astronautical Congress (IAC)*, Oct 2018.

[35] D. M. Boroson *et al.*, "Overview and results of the lunar laser communication demonstration," *Proc. SPIE 8971, Free-Space Laser Communiation and Atmospheric Propagation XXVI*, 6 March 2014. [Online]. Available: https://doi.org/10.1117/12.2045508

[36] A. Biswas *et al.*, "Status of nasa's deep space optical communication technology demonstration," in *International Conference on Space Optical Systems, Okinawa, Japan*, Nov 2017.

[37] R. T. Rajan, G. Leus, and A.-J. van der Veen, "Joint relative position and velocity estimation for an anchorless network of mobile nodes," *Signal Processing*, vol. 115, pp. 66 – 78, 2015. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0165168415000894

[38] G. Berkovic and E. Shafir, "Optical methods for distance and displacement measurements," *Adv. Opt. Photon.*, vol. 4, no. 4, pp. 441–471, Dec 2012. [Online]. Available: http://aop.osa.org/abstract.cfm?URI=aop-4-4-441

[39] R. T. Rajan and A. van der Veen, "Joint ranging and synchronization for an anchorless network of mobile nodes," *IEEE Transactions on Signal Processing*, vol. 63, no. 8, pp. 1925–1940, April 2015.

[40] Mars Cube One (MarCO). [Online]. Available: https://www.jpl.nasa.gov/cubesat/missions/marco.php

[41] C. Marrese-Reading, "Microfluidic electrospray propulsion(mep) thruster performance with microfabricated emitter arrays for indium propellant," in *52nd AIAA/SAE/ASEE Joint Propulsion Conference*, 2016.

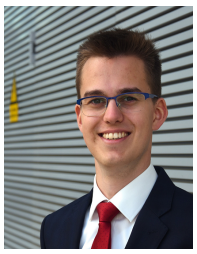
[42] F. Roybal, J. Banik, and T. Murphey, "Development of an elastically deployable boom for tensioned planar structures," in *48th AIAA Structures, Structural Dynamics, and Materials Conference*, vol. 1838, Apr 2007.

[43] J. A. Sanchez de la Vega and J. E. Velazco, "Q4 - A CubeSat Mission to Demonstrate Omnidirectional Optical Communications," in *IEEE Aerospace Conference Proceedings*, Mar 2020.

[44] S. Engelen *et al.*, "The road to OLFAR - a roadmap to interferometric long-wavelength radio astronomy using miniaturized distributed space systems," *64th IAC International Astronautical Congress*, 2013.

[45] K. Kelley, M. Elson, and J. Andrews, "Deploying 87 Satellites in One Launch: Design trades completed for the 2015 SHERPA flight hardware," in *29th Annual AIAA/USU Conference on Small Satellites*, 2015.

BIOGRAPHY



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