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Building Blocks for the Dark-Ages EXplorer (DEX): Enabling a Lunar Radio Telescope and Advancing Multi-Purpose Infrastructure for Sustainable Lunar Presence

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Abstract

The deployment of a large radio telescope array on the Moon represents a transformative leap for both scientific discovery and technological innovation. The Dark-Ages EXplorer (DEX) concept envisions a large-scale, low-frequency radio array on the lunar surface, capable of conducting groundbreaking observations of the early Universe. Achieving this ambitious goal requires an array of 1000-100,000 antennas, along with novel hardware and software platforms, posing significant engineering challenges. Historically, radio astronomy has been a catalyst for technological progress, and the advancements required for DEX could serve as foundational technologies for a wide range of applications. These innovations aim to enable new scientific discoveries while also supporting a sustainable human presence on the Moon and terrestrial applications. In this paper, we present key technological challenges identified in the recent Concurrent Design Facility (CDF) study, done in collaboration with the European Space Agency (ESA). Technological developments needed to bring DEX to reality have broader applications for future research and commercial activities on the Moon, including energy distribution, autonomous systems, thermal management, communications networks, software development, data management, signal processing, AI/ML and distributed optimisation. By addressing these challenges, we aim to foster cross-sector collaboration and accelerate the development of technologies essential for a sustainable and scientifically productive future on the Moon. Thus, DEX serves not only as an observatory but also as a building block for sustainable lunar exploration and development.

Keywords: radio astronomy, radio telescope, antenna design, multi-use infrastructure, sustainable lunar presence.

1. Introduction

Low-frequency radio astronomy represents the last major unexplored region of the electromagnetic spectrum. Observations below ~30 MHz from Earth are significantly affected by ionospheric absorption and the increasing impact of radio frequency interference from human activities. Yet this spectral window holds extraordinary potential as it carries the redshifted 21-cm line of neutral hydrogen from the first billion years of cosmic history, including the unexplored epochs known as the Dark Ages and the Cosmic Dawn [1]. Unlocking this window requires placing instruments in a truly radio-quiet environment.

The far side of the Moon is uniquely suited to this task. Shielded from terrestrial transmissions and free from an ionosphere, it offers the most pristine conditions in the inner Solar System for ultra-long-wavelength astronomy. The Moon also provides a stable platform for deploying large-scale interferometers, allowing transformative science that cannot be conducted from the ground or from near-Earth space.

The Dark-Ages Explorer (DEX) is a mission concept developed under ESA's Astrophysical Lunar Observatory (ALO) Topical Team study. Its goal is to detect the redshifted 21-cm signal from neutral hydrogen at redshifts $z \approx 12\text{-}80$, tracing the birth of the first stars, black holes and galaxies. By targeting both the global signal and, in the longer term, the spatial fluctuations of this line, DEX aims to fill a critical observational gap between the Cosmic Microwave Background and the capabilities of current telescopes.

Astronomy has historically driven technological innovations that have had broad societal and industrial impacts. Developments made for telescopes and

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detectors often find applications far beyond their original scientific purpose:

1) Noise reduction and correlation techniques from radio astronomy enabled the creation of Wi-Fi networks.
2) Charge-coupled devices (CCDs), developed for astronomical imaging, revolutionised consumer electronics, medical endoscopy and Earth observation.
3) Interferometric techniques advanced the design of ultra-stable atomic clocks, which underpin the GPS system and global financial networks.
4) Adaptive optics, originally designed to sharpen images of distant stars, is now widely used in ophthalmology for precision eye surgery.
5) Novel signal processing algorithms for scalable networks, particularly tackling challenges on positioning, timing and orientation of the deployed systems.
6) Data processing methods developed for large astronomical surveys laid the foundation for modern big data analytics and machine learning.

Similarly, beyond its scientific goals, DEX serves as a testbed for infrastructure development on the Moon. Many of the technical challenges required to build a lunar radio observatory mirror those faced by future lunar research and commercial activities, including the need for lightweight, deployable structures, autonomous robotic deployment over large areas, robust power distribution and energy storage systems, thermal management through extreme day-night cycles, and high-capacity communications and data handling. By addressing these challenges, DEX can catalyse the development of multi-use technologies, advancing both science and attempts for sustainable human presence on the Moon.

2. Scientific Motivation

The core science case for DEX is the detection of the redshifted 21-cm line of neutral hydrogen from the early Universe. This line provides the only direct probe of the Dark Ages and the Cosmic Dawn, epochs that remain observationally inaccessible with existing or planned facilities on Earth. Measuring the global 21-cm signal would reveal when the first stars and black holes began to heat and ionise the intergalactic medium, offering new insights into the thermal history of the Universe [1]. Extending this capability to map spatial fluctuations in the signal would enable astronomers to trace the clustering of the first galaxies, test models of dark matter and exotic physics, and study the growth of cosmic structure. In doing so, DEX would fill the gap between the last scattering surface observed by the Cosmic Microwave Background and the first galaxies imaged by telescopes so far, extending cosmology into an uncharted domain.

In addition to its primary cosmological goals, DEX would enable a broad range of complementary sciences. Low-frequency observations from the lunar far side can capture planetary radio emissions from the Solar System and beyond [2], providing a novel means of characterising planetary magnetospheres and habitability. The array can also be used to study heliospheric processes, such as solar particle storms and their interactions with the lunar environment, with direct relevance to space weather forecasting and plasma physics [3]. Furthermore, its sensitivity to ultra-long wavelengths would open discovery space for detecting radio transients, from exoplanetary aurorae to fast radio bursts, creating opportunities for serendipitous discoveries [4].

3. Technical Summary

As already mentioned, DEX is a concept for a scalable low-frequency radio interferometer, designed for deployment on the lunar far side. Its basic technical architecture, derived from a CDF study [5], is shaped by both the constraints and opportunities offered by ESA's Argonaut lander and current high-TRL technologies.

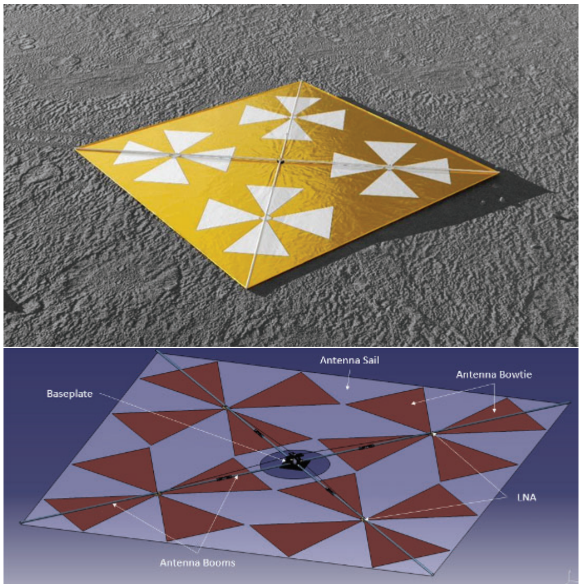

Fig. 1. Conceptual picture of the basic 4 x 4 antenna array of DEX: The antenna foil is held above the antenna plane by nonconductive inflatable supports, with power and data cabling routed below.

System Architecture and Deployment: DEX is based on modular sub-arrays of crossed-dipole antennas, each consisting of orthogonally oriented 3 to 5-m long dipoles (see Fig. 1). These lightweight, tubular-boom antennas are selected for their maturity and compact stowage on Argonaut, unfolding after landing. A rover deployed from Argonaut handles array installation: transporting sub-arrays, positioning them with the required accuracy, and ensuring connections with hubs and the base station. The minimum feasible system, a 4 x 4 array (16 antennas) plus a central hub (Fig. 1), can be delivered in a single Argonaut mission, with a total landed mass of ~1.1 t [6].

Power and Thermal Management: Power generation relies on solar arrays mounted on Argonaut's Cargo Platform Element (CPE), with distribution via series AC feed from hubs to antennas. Operations are limited to the lunar day, while regenerative fuel cells and insulation protect electronics during the extreme thermal swings of the lunar night (−170 °C to +90 °C). Low-noise amplifiers (LNAs), placed close to antennas, demand robust thermal reservoirs to prevent radio-frequency interference (RFI) and survive environmental stresses.

Data Handling and Communications: To minimise the traditionally heavy processing demands of interferometry, DEX adopts a Fast Fourier Transform (FFT) telescope architecture [7], where signals from a filled rectangular array are processed via 2D FFTs instead of full pairwise correlations. This reduces computational loads while preserving scientific capability. For the 4 x 4 array, daily science data volume is ~720 MB, processing requires ~102 GFlops, and transmission rate to Earth is only 0.6 kbit/s. Communications are relayed via existing or planned lunar infrastructure – Gateway, Lunar Pathfinder, or LCNS (Lunar Communications and Navigation Services), making DEX an early adopter of emerging cislunar networks.

Radio Frequency Protection and Spectrum Management: A central requirement for DEX is the protection of ultra-low-frequency radio bands from interference. The far side of the Moon is currently the only naturally protected radio-quiet zone in the inner Solar System. Maintaining this environment is essential not only for DEX's 21-cm cosmology science case, but also for long-term commercial and operational activities. Future lunar industries will rely on spectrum for communications, navigation, and IoT-like monitoring systems. By advancing a coordinated approach to spectrum management, DEX emphasises the importance of establishing protected astronomical bands alongside allocated industrial frequencies, thereby ensuring that science and commerce can coexist without mutual interference.

Scalability and Industrial Relevance: The initial Argonaut-delivered array would be capable of addressing the global 21-cm signal detection (named GloDEX experiment), while more ambitious science goals require ~1000 antennas (the 32 x 32 array; see Fig. 2) for studying the Cosmic Dawn, and even more antennas (256 x 256) would be needed for Dark Ages power spectra studies. Scaling the system to this level necessitates further innovation in ultralight deployable antennas, distributed low-power electronics and synchronisation networks, all of which have cross-sector value.

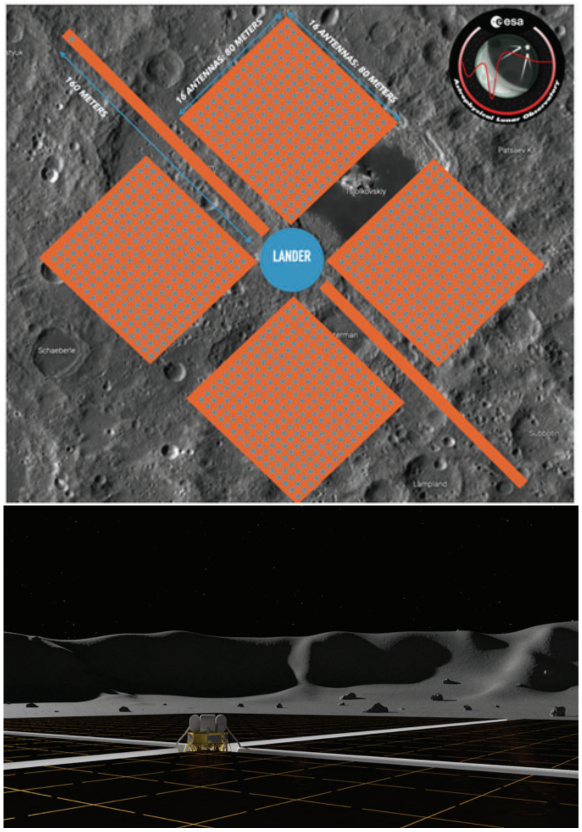

Fig. 2. Conceptual picture of DEX, consisting of a central hub/lander in the middle surrounded by four sub-arrays (32 x 32 antennas).

4. Building Blocks of Future Cislunar Development

The technologies required to realise the "full" DEX concept are not unique to astronomy, and they mirror the foundational capabilities needed for a broad range of lunar research and industrial infrastructure, making DEX a natural multi-use demonstrator.

One example is the need for low-mass, deployable structures. For DEX, lightweight antennas that can be compactly stowed during launch and deployed over large areas of the lunar surface are essential. In parallel, other lunar research and commercial activities will require similar deployable solutions for large solar arrays, thermal radiators and lightweight shielding to protect habitats and infrastructure from radiation and micrometeoroids. Development in one domain directly benefits the other.

DEX's reliance on autonomous robotic deployment of hundreds to thousands of antenna elements also aligns with the requirements for robotic construction of lunar bases, mining infrastructure and in-situ resource utilisation. The capability to operate rovers (e.g. LunarZebro [8]) and robotic arms with precision, adaptability and scalability in challenging terrain is a shared need that will underpin both scientific and industrial progress on the Moon.

Power distribution and storage represent another clear overlap. A DEX-scale interferometer requires a reliable energy supply across distances of up to a kilometre, a challenge similar to establishing modular microgrids for lunar outposts, processing facilities and extraction sites. Likewise, the need to survive the two-week lunar night pushes DEX toward energy storage technologies such as regenerative fuel cells or advanced batteries, which are equally vital for sustaining continuous industrial operations.

The mission also demands robust solutions for data processing, communication and autonomy. A large antenna array produces vast amounts of raw data that must be processed and transmitted efficiently, requiring distributed computing and optimised communications. These same systems are also required for navigation, teleoperations and coordination of autonomous assets by future lunar research and commercial activities. Similarly, the precise positioning required for correlating radio signals across a large array mirrors the navigation and surveying needs of prospecting and automated construction.

By investing in these shared technologies, DEX offers a pathway to advance both fundamental science and other lunar research and commercial activities, as well as human habitation. Just as the development of the James Webb Space Telescope (JWST) spurred deep-tech development, demonstrating the power of long-term investment and cross-agency collaboration [9], DEX can play a similar role by providing a platform for testing deployment mechanisms, thermal resilience, distributed edge processing and cislunar communications. As a tangible form of emerging lunar infrastructure, it can catalyse research and commercial investments, foster cross-sector partnerships and help define the operational backbone for future lunar science and commerce. In this way, DEX acts not just as an observatory, but as a building block for a sustainable lunar presence.

5. Conclusions

DEX is not only a science mission but also a technological pathfinder for the lunar research and commercial activities. The same innovations needed to realise DEX – lightweight deployable structures, autonomous robotic deployment across large surfaces, distributed power and communications, thermal management through the lunar night, and robust data networks – are directly relevant to the infrastructure required for lunar resource utilisation, construction and long-term human presence. In this sense, DEX serves a multi-purpose role: it aims to open a new cosmic window while simultaneously de-risking and accelerating the technologies that will enable sustainable research and commercial activities on the Moon.

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