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THE ROAD TO OLFAR - A ROADMAP TO INTERFEROMETRIC LONG-WAVELENGTH RADIO ASTRONOMY USING MINIATURIZED DISTRIBUTED SPACE SYSTEMS

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ABSTRACT

The Orbiting Low Frequency Antennas for Radio Astronomy (OLFAR) project aims to develop a space-based low frequency radio telescope that will explore the universe's so-called dark ages, map the interstellar medium, and discover planetary and solar bursts in other solar systems. The telescope, composed of a swarm of at least fifty satellites working as a single instrument, will be sent to a location far from Earth in order to avoid the high Radio Frequency Interference (RFI) found at frequencies below 30 MHz, originating from Earth. The OLFAR telescope is a novel and complex system, requiring not-yet proven technologies and systems, therefore, a number of key technologies are still to be developed and proven. Most of these can be tested on Earth, but four aspects in particular require in-space verification. Those are (1) the satellite's propulsion and attitude control systems, and (2) their interactions with the large science antennas, as well as the (3) payload system itself and finally (4) the in-space interferometry and 3D-imaging. Furthermore, the RFI environment in the intended target orbits is mostly unknown. Indeed, only three satellites missions have previously been launched into orbit shedding light on the RFI environment, but sufficiently detailed measurements allowing for the creation of a usable RFI model have never been performed. To carry out both the hardware qualification and RFI measurements, a few pathfinder missions are deemed in order. This paper describes these pathfinders in detail; outlining the scientific objective, the technologies being demonstrated as well as the missions' roadmap which revolves around a novel systems engineering approach. This approach resembles those used in certain fast-paced industries where development is heavily parallelised and products are launched as soon as opportunities arise. This will be combined with in-space upgrading of mission firmware to allow for high flexibility within the limited time and budget constraints of these pathfinders.

I. INTRODUCTION

The ultra-low frequency regime of 0.1- 30 MHz is one of the last unexplored bands in radio astronomy. Earth-based radio interferometry is severely limited in sensitivity at these low frequencies due to man-made Radio Frequency Interference (RFI) and ionospheric scintillation. The ionosphere scintillates below ~30 MHz and is completely opaque below ~10 MHz [1]. A space-based array of satellites, deployed above the Earths' atmosphere and far away from Earth itself, will be less hampered by these limitations and thus will open up this unexplored frequency regime.

The feasibility of a space-based array for long wavelength astronomy has been investigated in the past few decades via numerous studies, however all such endeavours were limited by technology (e.g. [2], [3]) The only successful mission to have investigated these long wavelengths is the RAE-B (Radio Astronomy Explorer – B) lunar orbiter in 1973, a single satellite which made astronomical measurements in 25 kHz to 13 MHz spectrum. Subsequently, this mission also provides us the only sky maps we have at these long wavelengths.

Since then, technology has advanced significantly. Previous studies, in particular the DARIS study [4], [2] have shown that with a modest budget of <500 M€, a formation of 9 satellites can be launched and operated, mapping the sky at frequencies ranging from 100 kHz to 10 MHz. The DARIS satellites were designed using readily available space grade technologies.

Orbiting Low Frequency Antennas for Radio Astronomy (OLFAR) is a feasibility study which investigates the challenges involved in designing and deploying a co-operative cluster of miniaturized satellites for interferometry at ultra-long wavelengths [5], [6], [7]. The OLFAR project is an attempt to develop a similar space-based telescope, using advanced Commercial Off-The Shelf (COTS) technologies, with a significant spin-in from mainstream technologies. Several technological breakthroughs have been achieved over the course of the project, yet a few issues remain open. This paper outlines the roadmap still to be taken in order to reach the final goal of an operational, high performance low frequency radio-telescope in space.

II. SCIENCE CASE

The exploration of the unknown territory that is low frequency radio astronomy is expected to yield extremely interesting science in a number of areas [1] lists a number of possible science cases for a low-frequency array of telescopes, those for which OLFAR will be particularly adapted are listed in this section.

Cosmological studies on the early universe, which include the Epoch of Reonization (EoR) and the dark ages in the 21-cm spectrum are a possible first case. Mapping and tomography require large baselines of the order of 20km whilst a very large number of antennas are needed to overcome the weak astronomical signals: two aspects which OLFAR aims to tackle. Another case is the surveying of galactic and extra-galactic large-scale radio sources such as galaxy clusters, radio galaxies, extremely red-shifted galaxies as well as planetary and solar bursts. Finally, surveying of galactic radio sources could provide valuable information regarding the origin of cosmic rays and surveys of the solar system neighborhood can be made.

As demonstrated in Table 1, the deployment location of OLFAR is not yet fixed; if however the Lunar orbit is used, an additional science case can be added to the list. This involves using the Moon as a detector for Ultra-High Energy (UHE) particles using emitted Cherenkov radiation as described in [8]. This is curently done from Earth using the LOFAR telescope; in-situ measurements provided by OLFAR would prove to be invaluable.

III. THE SYSTEM

In order to create any useful scientific instrument, certain specifications have to be met. The key driving parameters for OLFAR are listed in Table 1, adapted from [6]. As can be seen, the snapshot integration time is defined primarily by the relative speed of the satellites. This has been shown to be an issue for a lunar orbiting scenario [9], [10], as the relative speed in that case can reach values of over 100 m/s. This would limit the snapshot integration time to 1/100th of a second for signals with 1 m wavelength (i.e. at 30 MHz), which in turn would create data-sets too large to process and/or transmit ([11], [6], [12]).

Number of antenna nodes	≥ 10, scalable
Number of polarisations	3
Observation frequency range	0.3-30 MHz
Instantaneous bandwidth	≥ 1 MHz
Survey sensitivity	≤ 65 mJy
Spectral resolution	1 kHz
Snapshot integration time	1 to 1000 s, limited to $t_{int} \leq \left(\frac{1}{10}\lambda\right) / V_{relative}$
Maximum baseline between antenna nodes	100 km
Deployment location	High Earth orbit, Lunar orbit, Lunar L2, Earth leading/trailing

Table 1: OLFAR system requirements, adapted from [6]

Mainstream technologies have been gaining in capabilities, which currently surpass the capabilities of space-grade technologies. They are seen as the biggest enabler of an OLFAR-like mission, although their space-tolerance, and therefore their applicability in space will still have to be proven. Should such technologies be used however, the possibilities are almost limitless, as even common mobile phone platforms can achieve wireless transmission speeds in excess of 100 Mbps [13] and offer gigabytes of data storage, as well as computing powers in excess of 5.000 DMIPS per SoC [14], all at low power.

The OLFAR radio telescope would consist of a swarm of satellites [7], [6], [15] , each of which is equipped with a radio antenna payload and a payload processing module. The satellites form a swarm, in order to utilise a swarm's properties of almost indefinite expandability, which allows creation of a scalable system, as well as offer an increased availability ([16], [17]) and reduced management overhead.

In order to reach the required survey sensitivity, either a long mission duration, and therefore long per-spacecraft operational lifetime, or a large number of nodes is required. One advantage the use of a satellite swarm offers is that defunct satellites can also be replenished at some point during the active mission, in which case the system lifetime is increased through replenishing the system with fresh satellites, thereby increasing the system lifetime.

Both the miniaturization of electronics and other technology, as well as the increased robustness of a distributed instrument, and the cost of producing a larger number of satellites open the doors to the use of nano-satellite platforms for the OLFAR instrument nodes. The CubeSat standard with the plethora of readily available Commercial Off The Shelf (COTS) harware make adhering to this standard a valuable interest, especially regarding the design of the precursor missions discussed later.

The operational band of 0.3-30 MHz as defined by the key driving requirements requires antennas with lengths in the order of meters for each instrument node. Due to the large bandwidth, even these antennas will be electrically short, which gives rise to the preference of an omnidirectional receiving pattern for each of the nodes. The use of three orthogonal short active dipole antennas allows for the design of wide bandwidth, limited size antennas capable of achieving the scientific requirements. A length of 4.8 m for each dipole element (monopole) was set due to the effect of longer antennas on the RF properties [18] [19]. An overview is shown in Figure 1.

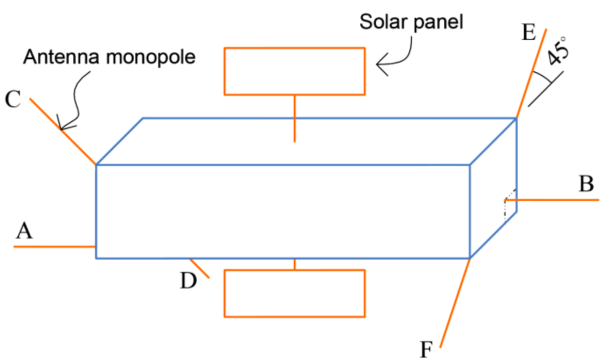

Figure 1: Antenna configuration on an OLFAR node

To integrate the monopoles into the nano-satellite platform of the OLFAR node, a deployment mechanism was developed. For a long stiff antenna that can be rolled up in a satellite, a tape-spring type antenna was designed. Each monopole consists of an extruded polymer tape-spring cross section with an embedded conductive element. Three of these wrappable antennas are stored in a single deployment subsystem, of whom two will be used per satellite. A deployment subsystem will be located at each end of the satellite, and deploy six monopoles orthogonally as depicted in figure (ref: configuration figure). A prototype of the deployment subsystem, shown in Figure 2, has been developed, along with its antennas. The system is CubeSat compliant (with some exceptions) and can therefore be made to work alongside available COTS hardware in any of the precursor mission(s).

Figure 2: OLFAR antenna deployment mechanism prototype

Besides to the monopoles for radio astronomical obsevation, antenna systems for the communication tasks will also be integrated in the CubeSat platform. Inter-satellite links (ISLs) and the downlink towards base station will be established by using non-deployable antennas. Planar radiating elements such as patches provide a good solution for the CubeSat scenario as they are characterised by reasonable gain figures while being small, robust and very easy to integrate.

Furthermore, appropriate algorithms will be employed to support the physical layer into fulfilling the communication requirements. The ISLs will use one antenna on each facet of the CubeSat, and a combining scheme that maximizes the gain in the direction of transmission [20]. The swarm-to-Earth communication will require a smaller number of antennas per satellite as it will take advantange of the antenna diversity that the swarm has to compensate for length of the communication link, and for the random orientation of the satellites [21].

For accurate radio astronomy imaging, inter-satellite communcation and collision avoidance , the position and timing of the OLFAR satellites must be known to a fraction of the observation wavelength [6] . Moreover, the relative position and relative synchronization between the satellite nodes suffice the needs of the OLFAR system. Given the far away deployment location (from Earth) and the large number of antennas, the OLFAR network will be a co-operative network with minimal communication with Earth based ground stations. Thus, localisation and synchronisation of the OLFAR satellites is a boot-strap problem, which must be dynamically solved by the OLFAR system.

For accurate timing, all satellites will be equipped with chip scale Rubidium clocks [22], which enables us to approximate the clock output as a first order model with unknown clock offset and clock skew, for a short duration in time. Thus, assuming this affine clock and the positional stability of the satellites within desired accuracies, the unknown pairwise distances and the clock parameters can be jointly estimated via two-way ranging [23]. The relative locations can be estimated from these distances using Multi-Dimensional Scaling.

Furthermore, when the satellites are in motion, the pairwise distances between the satellites can be modelled as polynomial in time. In which case, for a first order distance model [24], second order distance model [25] and more generally for any order of approximation, the time varying distances along with the clock parameters can be estimated using closed form solutions [26]. A step further, the relative velocity can also estimated be as shown in [27] [28].

IV. OPEN ITEMS

The primary reason for placing the telescope in space is to avoid man-made and natural emissions at low frequencies. NASA launched two satellites into Earth orbit, and later Lunar orbit to asses the presence of radio astronomical signals at low frequencies. Also the WAVES instrument, flown aboard the WIND [29] and STEREO [30] satellites is currently sampling the low frequency environment. This data however is not sufficiently detailed to allow extracting RFI mitigation methods for the OLFAR radio telescope. Moreover, as the deployment location of OLFAR also depends on the RFI level, which determines the required sensitivity of the instrument, a tomographic view of the RFI environment near Earth is deemed invaluable.

The intention is to place the radio telescope in a location which is remote enough to avoid RFI, and also far enough from popular orbits, in order to avoid collisions. Also debris mitigation is crucial, as launching a large number of satellites has the potential of creating a lot of space debris. In order to maximise the useful data volume, this location is preferably as close as possible to Earth, hence an optimum can be established in terms of range. The RFI environment will therefore act as a lower limit to the range, whilst the communication link distance will serve as an upper limit. It is therefore imperative that an accurate picture of the RFI environment in Earth proximity is formed. Most of the precursor missions foreseen will therefore carry at least one instrument designed to achieve this goal.

One of the most challenging issues on the OLFAR system is the data processing and distribution. Few imaging algorithms exist for antennas which are not coplanar, and of those that do exist, the processing and transfer bandwidths required are significant [31]. OLFAR will therefore only corellate the data of each individual antenna in space, and all further imaging will occur on ground [11]. The fact OLFAR consists of a swarm will likely result in missing baselines, due to satellite malfunctions, in which case imaging could perhaps be salvaged using compressed sensing methods [32]. No 3D imaging has, to the best of the author's knowledge, been performed to date, and this area will therefore require a significant amount of research. Also the correllation of the data will still have to be optimised, and preferably distributed more evenly, in order to map more optimally onto the swarm architecture.

Given the cost involved in launching satellites, reducing the per-satellite mass for OLFAR is paramount. Low mass satellite platforms, such as nano-satellites are only just starting to apply orbit correction thrusters and attitude and orbit determination systems. For OLFAR, proving that orbit maintenance for an invidivual satellite works, and more importantly, is reliable enough for long-term operations is quite relevant, especially given that for a reduction in operation cost, a mostly autonomous system is considered to be highly desirable. This, to date, has not been attempted on very small satellites. Also the interaction of the attitude and orbit control system with the large science antennas can prove to be problematic, as the antennas will act as large springs, possibly destabilising the control mechanisms.

And lastly, no satellite swarms have been flown to date. Swarm management with Earth-based mobile platforms is being investigated, yet for space-based swarms, which require complex and precise orbit correction manoeuvres which is still unproven.

V. ROADMAP

In order to prove certain key aspects, required for OLFAR, quite a few precursor missions are foreseen. These will fly under the working title eMoth, named after "electronic moths", purposefully flying into traps like the Van Allen radiation belts. The reason for testing various aspects in different missions is twofold: firstly to gain experience with each of the aspects whilst decoupling the various impacts on each other as much as possible. This is primarily done through taking small steps in the developments. Secondly, this allows for improvements in the procedures for manufacturing and launching nano-satellite platforms: experiences learnt at each of the steps will be taken into account in the next step, thereby improving the chance of success, as well as reducing the cost through avoiding making the same mistakes.

eMoth 0: Testing propulsion and orbit control

The first aspects which have to be validated are (autonomous) orbit control for a nano-satellite. The first satellites will therefore primarily test orbit control algorithms and sensors, as well as validating lifetimes and performances of the thrusters envisaged. This mission will also test the utility and ease of integration of the basic platform. The advantage of this satellite is that it can be launched into any available orbit, as long as the orbit crosses the primary ground station for controlling and monitoring of the experiment.

eMoth 1: Getting to know the environment

Secondly, the typical RFI levels and types will have to be determined, in order to allow creation of (on-line) RFI mitigation strategies. Also the minimum required sampling bit depth for OLFAR depends on the RFI level, as well as the number of bits to be transmitted. This has an effect on the required data-rates of the satellites, as in case no RFI compensation can be performed on-line, all sampled bits will have to be transferred to Earth for post-processing. This significantly increases the required data-rate, which in turn will favour orbits close to Earth. Orbits closer to Earth are also expected to show stronger RFI levels, hence an optimum will have to be established. Therefore, the second mission will test unfolding science antennas, as well as establish functionality of the payload receiver chain. Interactions of the antennas with the local plasma will be investigated, and of course the background levels will be sampled and transmitted in full. The intention is to place a single satellite into a GTO orbit, in which it will stay. GTO is chosen both for the relatively high availability in terms of piggy-back launches, as well as the high eccentricity, which would allow for the creation of a 3D (tomographic) view of the RFI environment over time. Moreover, payload data storage and processing in a harsh environment can be validated, as GTO orbits traverse the Van Allen radiation belts twice per orbit. This mission will therefore also act as a technology demonstrator for operation of the envisaged mainstream electronics in space.

eMoth 2: Interferometry and swarm management

Once a picture of the RFI environment near Earth has been established, the payload data processing, as well as the RFI mitigation strategies can be validated. Therefore, at least 3 satellites will have to be launched into a favourable or representative orbit, allowing preliminary science data collection and interferometry to take place, while testing RFI mitigation strategies as well as rudimentary swarm management strategies, controlling the satellites.

OLFAR 0: The first segment of the OLFAR array

At this point, the first OLFAR satellites can be built and tested. It is commonly accepted that 5 satellites would be required to form the first useful images. Lessons will undoubtedly be learnt during design and construction of these satellites, as well as throughout their life cycle, which can be taken into a next iteration of the design of OLFAR satellites. These first 5 satellites however will allow performing useful radio astronomy, and will therefore act as the first segment of the OLFAR telescope.

OLFAR: Gradual build-up

Given the lessons learnt up to this point in time, revised OLFAR satellites can be built and launched. Given that OLFAR is a swarm, and swarm management should be in place at this point, any satellites launched at any given point in time should seamlessly be able to join the swarm and augment the science data collection process. This procedure would also be used to replace defunct satellites throughout the mission, should the need arise. From this point on, the array can be completed, or expanded, depending on the level of funding available, as well as the available launch opportunities.

Roadmap

These missions have been aligned in a time sequence, shown in Figure 3. T_0 represents the official starting date of the project. The intention is to launch a new stage in the roadmap every 2-3 years, although intermediate steps are allowed. This roadmap is quite ambitious, even when using off-the-shelf technologies, so delays can be expected. When all satellite developments are ran as parallel projects however, the delay in one step of the roadmap does not have to have a significant impact on the next steps. Lessons learnt however will prove crucial, hence some delays are to be expected overall.

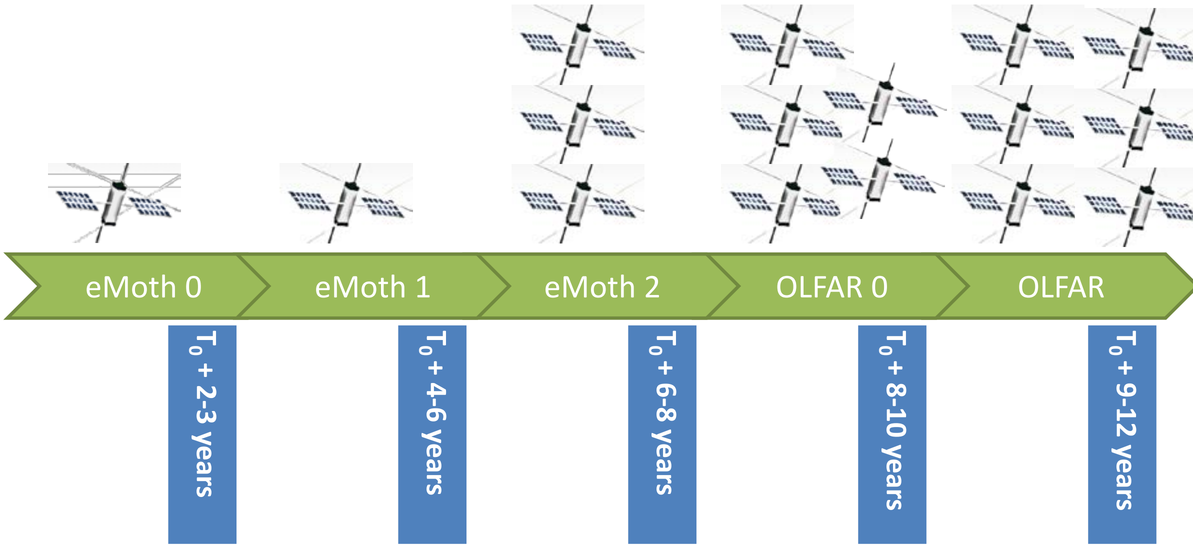

Figure 3: The Road to OLFAR

VI. CONCLUSIONS

Low frequency radio astronomy will present a new milestone in our understanding of the universe. Missions like OLFAR are required to permit access to this regime of the spectrum, yet quite some technological challenges still lie ahead. The road towards realisation of OLFAR is therefore open, but certain key milestones will have to be reached prior to being able to launch OLFAR. This paper has identified some of the challenges and missing links still ahead, and proposed a roadmap of precursor missions with the related research goals to do so.

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